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Planetary Atmospheres 1958-1964

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Significant Achievements in

Planetary Atmospheres 1958-1964

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Foreword

THIS VOLUME IS ONE OF A SERIES which summarize the progress made during the period 1958 through 1964 in discipline areas covered by the Space Science and Applications Program of the United States. In this way, the contribution made by the National Aeronautics and Space Administration is highlighted against the background of overall progress in each discipline. Succeeding issues will document the results from later years.

The initial issue of this series appears in 10 volumes (NASA Special Publications 91 to 100) which describe the achievements in the following areas: Astronomy, Bioscience, Communications and Navigation, Geodesy, Ionospheres and Radio Physics, Meteorology, Particles and Fields, Planetary Atmospheres, Planetology, and Solar Physics.

Although we do not here attempt to name those who have contributed to our program during these first 6 years, both in the experimental and theoretical research and in the analysis, compilation, and reporting of results, nevertheless we wish to acknowledge all the contributions to a very fruitful program in which this country may take justifiable pride.

HOMER E. NEWELL
Associate Administrator for
Space Science and Applications, NASA

Preface

A SIGNIFICANT ADVANCE in understanding the Earth's atmosphere has been achieved in the years 1958–1964 as a result of experiments conducted from satellites and sounding rockets and a supporting program of laboratory and theoretical research. New information concerning the atmospheres of the other planets has been acquired and the next few years hold great promise for direct investigation of the atmosphere of Mars.

This report is concerned with the present status of knowledge and the results that have been obtained on the Earth's atmosphere above approximately 30 kilometers in altitude, and on the atmospheres of the other planets, in particular, Mars and Venus. It is also the purpose of this report to discuss the current problems in this discipline and to indicate the direction of future research efforts as it appears at this time.

Probably the greatest change in our understanding of the Earth's upper atmosphere is recognition of the variability in structure and composition that occurs with changes in latitude, altitude, time of day, season, and solar cycle. It is now recognized that some important atmospheric processes occur under conditions considerably removed from equilibrium, and our theories must be modified to account for these effects. The upper atmosphere has been found to be quite responsive to external energy inputs, principally, but not exclusively, of solar origin. The following items represent a selection of significant advances in somewhat more detail.

The temperature of the isothermal region (altitudes above about 300 kilometers) of the atmosphere has been found to be variable, ranging from 700° to 1800° K and higher, depending upon time of day, solar activity, sunspot cycle, latitude, and time of the year.

Electron temperature in the F-region and above has been found to exceed neutral-particle temperature during the daytime, especially in the early-morning hours.

The altitude at which molecular diffusion begins to become important in determining the distribution of atmospheric constituents has been well established at about 105 kilometers.

Hydrogen and helium have been found to be important constituents of the Earth's outer atmosphere. The density of the atmosphere at these extreme altitudes is much greater than previously believed.

The density of the upper atmosphere has been found to vary in the same manner as temperature, but with larger relative amplitude. A diurnal bulge exists on the daytime side of the Earth, with the maximum occurring in the early afternoon.

Strong wind-shear zones have been found in the region from 70 to 120 kilometers. At about 150 kilometers, the winds appear to be equatorward, although the details are not clear.

Rocket observations have confirmed the existence of a hydrogen geocorona, forming the outermost portion of the Earth's atmosphere.

The role of atomic and molecular oxygen and nitrogen in airglow processes is becoming better understood. The equatorial red arc, due to the oxygen red line, correlates well with electron concentration at the F_2 peak.

Rocket measurements have confirmed the belief, based on ground measurements, that bright auroral emissions are excited by energetic electrons, while proton-excited auroras are more diffuse and extensive. Contrary to earlier ideas, it is now recognized that, rather than being a source of auroral electrons, the Van Allen belt receives and traps some auroral electrons that are energized by some mechanism as yet unknown.

Micrometeoroid-impact rates have been determined by many space vehicles. A decrease in impact rate has been found in interplanetary space away from the Earth's vicinity. Although there are great variations in impact rates, because of the presence of streams of particles in interplanetary space, an enhancement of 100 000 near the Earth, due to the Earth's gravity field, is indicated. Measurements of zodiacal light indicate that micrometeoroids are the major contributor, the contribution from electrons in interplanetary space being negligible by comparison.

Recent work indicates that the atmospheric pressure at the surface of Mars is more likely about 25 millibars than about 85 millibars, the formerly accepted value. Carbon dioxide is known to be a prominent constituent of the atmosphere. The amount of water vapor in the atmosphere is very small, but ice probably forms the polar cap.

Spacecraft and ground-based measurements indicate that the surface of Venus may be as hot as 700° K and that the surface pressure of the atmosphere may be of the order of 10 atmospheres or greater. The nighttime temperatures should be approximately equal to the daytime temperatures.

Future steps in extending our understanding of atmospheric processes are to conduct more detailed investigations of what occurs in the polar regions, and to continue investigation of the temperate and equatorial regions, with particular emphasis on simultaneous determination of the energy inputs responsible for atmospheric phenomena, principally solar electromagnetic and particulate radiations. The roles of internal gravity waves and large-scale circulation patterns remain to be defined in detail, although the importance of these phenomena now appears well established. The flight-experiment program must continue to be supported by a vigorous laboratory program, to investigate the physical processes and to determine the reaction constants needed to interpret flight results. Likewise, a strong theoretical program is essential to stimulate further research and to transform flight and laboratory results into a quantitative understanding of atmospheric processes.

At the present time, we have only a fragmentary description and understanding of the atmospheres of the other planets. Major attention in succeeding years will be directed to understanding the atmospheres of Mars and Venus through direct space-probe research. The surface pressure of the Martian atmosphere and the magnitude and character of winds near the surface are critical parameters for the design of survivable landing capsules. There is uncertainty of an order of magnitude or more in present estimates of the surface pressure, and present estimates of wind velocities indicate disturbingly high values from a capsule-landing viewpoint. It is expected that data obtained by ground-based observations of Mars during the last opposition and currently being reduced will narrow the uncertainty concerning the surface pressure.

This preface and the summary were prepared by the Planetary Atmospheres staff, Office of Space Science and Applications, who also edited the complete report. The chapters were written by Francis S. Johnson.

Contents

chapter 1

Highlights of Research

EARTH

Atmospheric Structure

Temperature

IT HAS BEEN FOUND that the temperature distribution of the upper atmosphere becomes isothermal above about 300 kilometers. The temperature in this isothermal region has been found to be variable, ranging between extreme limits of about 700° and 1800° K, but occasionally higher. There is a diurnal variation, with the maximum daytime temperature about 1.33 to 1.50 times the minimum nighttime temperature. There are variations from day to day that correlate well with solar activity and geomagnetic variation. There are annual and semiannual variations, the causes of which are not well understood. The longest term and largest amplitude variation is associated with the sunspot cycle. There is also a latitudinal variation.

The temperature at the mesopause is variable, generally having its maximum value at high latitudes in winter and its minimum in summer. At high latitudes in summer, the temperature is especially low, near 140° K. These very low temperatures are associated with the presence of noctilucent clouds.

The electron temperature was found frequently to exceed the neutral-particle temperature in the ionospheric F-region and above. The difference is especially pronounced in the early-morning hours.

Composition

The importance of molecular diffusion in the gravitational field in controlling the distribution with altitude of atmospheric constituents has become well established during the past 6 years. The disturbance of the diffusive-equilibrium distribution by diffusive flow has been evaluated for atomic hydrogen, and the problem is now being solved for atomic and molecular oxygen. In the lower thermosphere, eddy diffusion is more important than molecular diffusion.

Atomic hydrogen has been found in the outer atmosphere, contributing to a geocorona that surrounds the Earth. After the discovery of hydrogen, helium was found. While this does not extend as far into space as the hydrogen does, there is an extensive region, variable with temperature (and hence especially with the sunspot cycle), where helium is the predominant atmospheric constituent.

Density

The pattern of atmospheric-density variation is similar to that of the temperature variation, but it is of much larger relative amplitude. Thus, a diurnal bulge exists on the daytime side of the Earth, with the maximum in early afternoon. The density at extreme altitudes is much greater than was anticipated before the discovery of helium and hydrogen in the geocorona.

It has been found that the density increases in the upper atmosphere associated with magnetic activity over the winter polar region are greater by a factor of 3 or 4 than those at lower latitudes.

Atmospheric Motion

Strong shear zones have been found to exist in the region from 70 to 120 kilometers. These have been most reasonably explained as internal gravity waves that originate in the lower atmosphere and increase greatly in amplitude as they propagate upward. Other manifestations of internal gravity waves have been found in temperature oscillations with altitude in the ionospheric E-region, in the occurrence of sporadic E in strong shear regions, and in traveling disturbances in the ionosphere.

Some evidence has been found for large-scale circulation of the atmosphere, and such circulation is certainly to be expected as a result of the latitudinally nonuniform heating of the upper atmosphere. The details of the circulation are by no means clear, but near 150 kilometers the winds appear to be equatorward.

Airglow

The existence of a hydrogen geocorona around the Earth has been demonstrated on the basis of hydrogen Lyman-alpha observations made from rockets. The hydrogen emissions (H-alpha and Lyman-alpha) in the upper atmosphere result from fluorescence, or from scattering of solar radiation; in addition, an extraterrestrial component of the Lyman-alpha radiation has been identified.

The vertical profiles of dayglow emissions from atomic oxygen at 1304 and 6300 Å and atomic nitrogen at 1200 Å have been observed in rocket flights.

New concepts have been developed on excitation mechanisms for nightglow emissions. The oxygen green line cannot be directly excited by a three-body, atomic-oxygen recombination process, but probably results instead from a two-step process, in which the excitation energy is transferred from a recently recombined oxygen molecule to an oxygen atom. The oxygen red line correlates well with the electron concentration at the F_2 peak, suggesting an ion-recombination mechanism for excitation. In some cases, the red line is apparently excited by an elevated electron temperature.

Rocket measurements have confirmed inferences from ground measurements that bright auroral emissions are excited by energetic electrons, while proton-excited auroras are more diffuse and extensive. The spectra of auroral electrons are much softer than those of Van Allen electrons. Although it was thought for a while that the source of auroral electrons was the Van Allen belt, now it is recognized that the reverse is more nearly true. Some unknown mechanism energizes the auroral electrons, and a few of these, especially at higher energies, become trapped in the geomagnetic field and become a part of the radiation belt. Auroral current systems have been explained on the basis of the diurnal distortion of the magnetosphere, and the consequent separation of trapped charged particles and the outer-ionospheric charged medium that normally neutralizes the trapped particles.

METEOROIDS

Micrometeoroid-impact rates have been measured in many space vehicles, and the rate at the top of the atmosphere is not alarming, about 6×10^{-6} particles/m^2/sec/sr. The rate of penetration of thin structural members has been observed to be less than that predicted from the impact data, about 3×10^{-8} penetrations/m^2/sec for 25-μ thicknesses. There is a diminution of the impact rate upon moving away from the Earth's vicinity, indicating an enhancement of about 100 000 near the Earth, due to the Earth's gravity field. There are great variations in the impact rates, owing to the presence of streams of particles in interplanetary space. Many of these have been charted.

Micrometeoroids in space scatter sunlight, which is recognized on Earth as zodiacal light. Measurements of the zodiacal light indicate that it virtually all originates in this way, the contributions of electrons in interplanetary space being negligible by comparison.

Noctilucent clouds form near 80 kilometers at high latitudes in summer, and it has long been conjectured that they might consist either of ice crystals or of meteoric dust.

Measurements in rockets seem to confirm that dust with diameters of a few tenths of a micron is sometimes present under these conditions, but that ice probably forms on the dust particles to produce the clouds.

MARS

Recent examination of old spectral data indicates that the surface pressure on Mars is less than formerly accepted, the former figure being based mainly on optical scattering data. The pressure is probably about 25 millibars rather than 85 millibars, and CO_2 is a very prominent, possibly predominant constituent. The amount of water on the planet appears to be very small, but ice probably forms the polar cap.

VENUS

Radio emissions from Venus first indicated that the surface of the planet might be very hot, perhaps 700° K. The atmosphere is very hazy, and the levels to which one can see are high and cold, and very little water vapor can exist in the region that is easily seen. The total water vapor remains in question. The planet apparently turns slowly and possibly synchronously with its rotation about the Sun, so Coriolis forces play a very small role in atmospheric motion. The high-density atmosphere is able to transfer heat effectively to the dark side of the planet with very modest velocities, of the order of 1 m/sec, keeping the nighttime temperatures approximately equal to the daytime. The surface pressure is of the order of 10 atmospheres or greater. Mariner data have been valuable in establishing the above description.

JUPITER

Spectroscopic measurements have identified molecular hydrogen as the principal constituent of the Jovian atmosphere.

chapter 2

Results of Research

THE RESULTS OF 6 YEARS OF RESEARCH effort in planetary atmospheres, starting with the formation of NASA in 1958, are summarized here. Most of the results relate more to the Earth than to the other planets, but significant results relating to Mars, Venus, and Jupiter have also been obtained and are briefly discussed. In many cases, important new concepts have been established, while in others the descriptions of atmospheric properties have been greatly improved, without alteration of the fundamental concepts of atmospheric behavior.

EARTH

Accomplishments relating to the Earth's atmosphere are described below under three separate headings: atmospheric structure, atmospheric motion, and airglow.

Atmospheric Structure

The structure of the atmosphere is most appropriately described in terms of the distributions of temperature and composition. These control the distribution of density, which is the parameter in terms of which the atmosphere is most directly described by observational data.

Temperature

During the past 6 years, a fairly complete picture of the temperature structure of the upper atmosphere has emerged. Although several important points remain in doubt, especially in connection with latitudinal distributions and their variations, these should also be resolved within the next few years.

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Spitzer (ref. 1) originally recognized that the outer portion of the atmosphere (above approximately 300 kilometers) should be isothermal, but the concept was not widely accepted until Nicolet (ref. 2) restated the theoretical basis and Kallmann Bijl (ref. 3) stated that experimental data were in agreement with the theory. The reason for the isothermal upper atmosphere is that the energy absorbed at very high altitudes, where the atmosphere is extremely rarefied, is small compared to the amounts of heat that can be conducted by the upper atmosphere when even small temperature gradients are present (the thermal conductivity is not changed by increasing rarefaction of gases, but the capacity for energy absorption is reduced). Typical temperature distributions through the atmosphere are shown in figure 1 for nighttime conditions near the minimum of the sunspot cycle, for daytime conditions near the maximum of the sunspot cycle, and for an intermediate situation (ref. 4). It is now frequent practice to characterize the atmosphere in

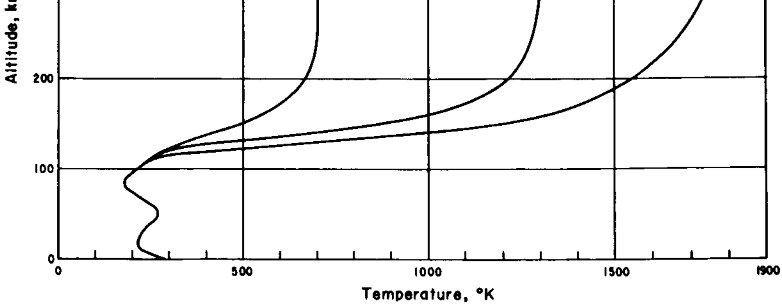

Figure 1.—Typical temperature distributions for nighttime conditions near sunspot minimum, for daytime conditions near sunspot maximum, and for an intermediate situation.

terms of the temperature in the isothermal region. Since the isothermal region extends into the exosphere, the temperature may also be referred to as the exospheric temperature.

The exospheric temperature has been found to be more variable than was anticipated in 1958, and a number of systematic time variations have been found. One of these is the diurnal variation, which shows a maximum in early afternoon, at about 1400 hours, and a minimum just before sunrise, at about 0500 hours. The daytime maximum is larger than the nighttime minimum by a factor that lies between 1.33 (ref. 5) and 1.50 (ref. 6). The diurnal variation results from the interruption during the night of the heat input into the upper atmosphere by absorption of solar ultraviolet radiation. The course of the diurnal temperature curve is shown in figure 2 (ref. 7) for several levels of solar activity.

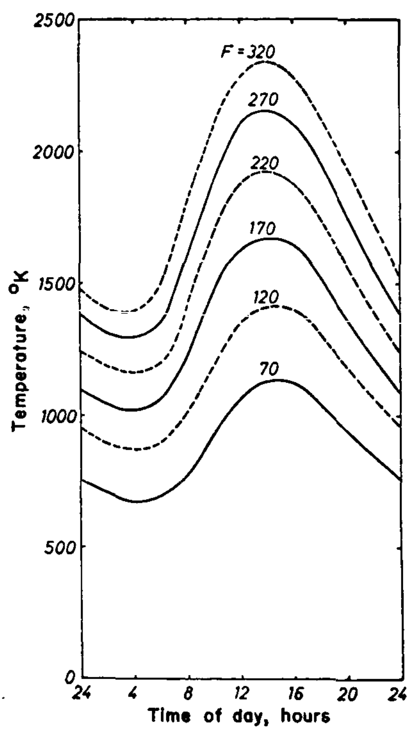

Figure 2.—Diurnal temperature variations for several levels of solar activity (Paetzold, 1963). The index of solar activity, *F*, is the 10.7-centimeter solar radio-noise flux in units of 10^{-22} W/m^2/cps.

Another variation in exospheric temperature is associated with solar activity, for which the 10.7-centimeter solar radio-noise flux received at the Earth's surface is probably the most-used index. Figure 3 shows the variation of the 27-day average of the 10.7-centimeter solar radio-noise flux over the course of a sunspot cycle. The solar radio-noise flux and the exospheric temperature have a lower correlation on a day-to-day basis, but longer term trends are identifiable. There are 27-day recurrent tendencies associated with the rotation of the Sun, and

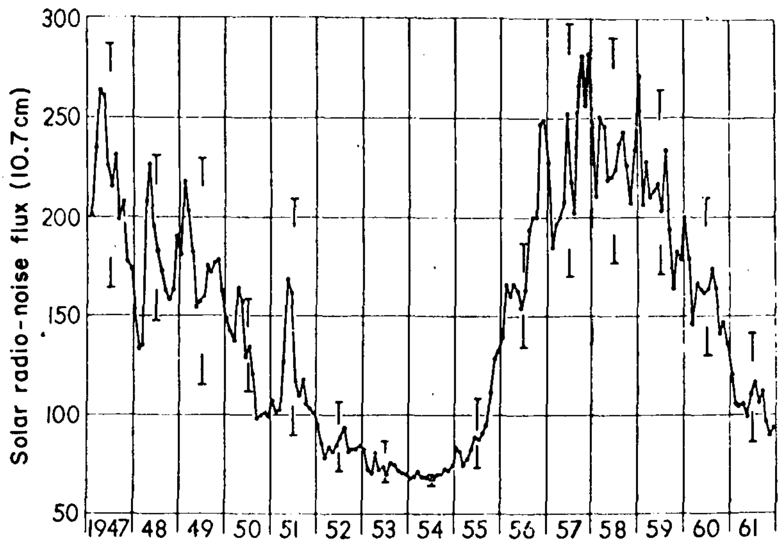

***Figure 3.*—Variation of the 27-day average value of the 10.7-centimeter solar radio-noise flux through a sunspot cycle. Also indicated are the annual maximum and minimum values.**

there is an 11-year variation that is in phase with the sunspot cycle. Figure 4 shows the long-term variation in exospheric temperature with solar radio-noise flux, using 27-day averages to smooth the day-to-day variations (refs. 8 and 5). The day-to-day variations in exospheric temperature are less strongly dependent upon the day-to-day values of the 10.7-centimeter solar radio-noise flux than are the long-term temperature variations dependent on the 27-day averages of the solar radio-noise flux (ref. 8). Except near the minimum of the sunspot cycle, the slope of the nighttime curve shown in figure 4 is about 4.5° C per unit of solar radio-noise flux (10^{-22} W/m^2/cps), whereas the day-to-day variations are about 2.5° C per unit deviation of solar radio-noise flux from the 27-day average value. To obtain the temperature for any given day, the 27-day average for the solar radio-noise flux should be obtained for the interval centered on the day in question, and figure 2 should be used to convert this value into an average nighttime value for the temperature. The difference between the daily and 27-day average values of the flux then should be multiplied by 2.5 and applied as a correction to the average temperature to get the minimum nighttime temperature appropriate to the day in question.

The maximum range of exospheric temperature is very substantial, as can be seen from either figure 2 or figure 4. Nighttime temperatures near sunspot minimum are about 700° K, whereas average daytime temperatures near sunspot maximum are about 1800° K. Further, during periods of particularly strong solar activity near sunspot maximum, temperatures may occasionally rise well above 2000° K, but this appears to happen only for brief intervals of about a day in length.

There is generally good agreement among the exospheric temperatures determined by different workers. Harris and Priester (ref. 6) have shown that their de-

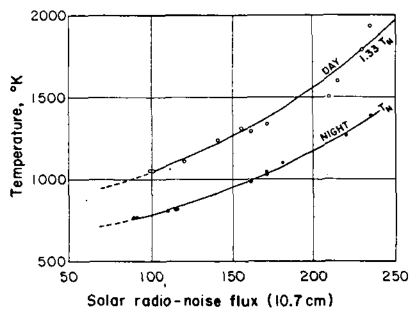

Figure 4.—Average exospheric temperature as a function of the 10.7-centimeter solar radio-noise flux, both averaged over 27-day intervals (ref. 5). The units for the noise flux are 10^{-22} W/m^2/cps.

terminations, based upon orbital-decay data obtained by King-Hele (ref. 9), agree within a few percent with the determinations of Jacchia (ref. 8) for nighttime, but that their daytime-maximum values are consistently higher than Jacchia's, sometimes by as much as 15 percent. Paetzold's (ref. 7) values generally lie close to Harris and Priester's (ref. 6) for the daytime, but are slightly below for the nighttime. This generally good agreement among independent investigators for the value of the exospheric temperature suggests that the determinations are accurate to within 10 or 15 percent. The values have been further confirmed by sodium-vapor-trail measurements (ref. 10).

Although the 10.7-centimeter solar radio-noise flux is the most-used index of solar activity, Nicolet (ref. 11) has found that the 8-centimeter flux has more desirable properties, in that the exospheric temperature is a linear function of the 8-centimeter flux, whereas significant departures from linearity occur for the 10.7-centimeter flux below 150 units, as can be seen in figure 4.

The temperature maximum at 1400 hours, shown in figure 2, is frequently referred to as the diurnal bulge, because the atmosphere is more extended in the vertical direction where the temperature is high. Jacchia (refs. 12 and 8) describes it as a symmetrical (circular) bulge, centered approximately 30° of longitude to the east of the subsolar point; i.e., its center occurs at the latitude of the subsolar point but lags about 2 hours behind it. It is not clear whether the description "symmetrical" is appropriate to latitudes higher than about 60°; the polar regions remain the least-well-observed portion of the upper atmosphere.

The exospheric temperature shows a variation that is correlated with magnetic activity. At temperate and low latitudes, the temperature in degrees centigrade is increased beyond the value indicated above by an amount that is numerically approximately equal to the planetary magnetic index, a_p (ref. 5). On the one occasion where the perigee of a suitable satellite orbit was located over a polar region, which was the winter pole, the temperature change was four times greater than at low latitudes (ref. 5). This indicates that upper atmospheric heating associated with magnetic activity is more pronounced in the polar regions than at lower altitudes, at least in the winter polar region. This heating might be due to energetic particles impinging upon the upper atmosphere at high latitudes, or to absorption of hydromagnetic waves, the magnetic variations at high latitudes being especially large.

Annual and semiannual variations in exospheric temperature have been identified (ref. 7), although there is no generally accepted explanation for these variations. The annual variation shows a maximum in January and a minimum in July, with an amplitude of about 100° C. The phase of this variation suggests that it is caused by the Earth's varying distance from the Sun, but the amplitude is too great for this explanation to be adequate. The semiannual variation shows maxima in early April and October, and minima in January and July. The amplitude is about 200° C near the maximum of the sunspot cycle and 100° C near the minimum. Johnson (ref. 13) has suggested that the semiannual variation results from dynamical effects of the general circulation of the atmosphere; if the circulation at the equinoxes is less favorable for the transfer of heat from the upper thermosphere to the mesosphere than is the circulation at the solstices, then the exospheric temperature should have a maximum value at the equinoxes. It is possible that the annual variation is also dynamical in origin.

The solar energy that is absorbed in the upper atmosphere does not all appear as thermal energy, as some of the energy is used in dissociating molecules and in forming ions. When ions are formed, photoelectrons are ejected with varying amounts of energy, and they can share this energy more readily with the ionospheric electrons than with ions, atoms, or molecules. This results from the fact that the large mass ratio between electrons and heavy particles is unfavorable for energy exchange. Consequently, the electrons are frequently characterized by a higher temperature than the neutral particles (refs. 14–16). The effect is most pronounced at the higher altitudes (above 150 kilometers), where collisions between electrons and neutral particles are so infrequent that they are not very effective in transferring excess energy. It is also pronounced when the electron concentration is particularly low while in the presence of solar ionizing radiation, as it is just after sunrise. It is not uncommon to find the electron temperature many hundreds of degrees above the neutral-particle temperature above 200 kilometers, even a factor of 2 higher (refs. 17–19). The biggest difference is observed just after sunrise (ref. 20). The difference is small or absent at night.

Interesting temperature variations have also been observed in the mesosphere and lower thermosphere. During the winter at high latitude, the temperatures are fairly high and rather irregular in vertical distribution, the temperature being near 250° K (refs. 21 and 22). During the summer, the temperature minimum at the mesopause becomes very pronounced at high latitudes, the temperature falling to about 140° K (W. Nordberg, private communication). Since such low temperatures seem to be associated with the presence of noctilucent clouds at high latitudes in summer, it appears probable that ice plays an essential role in their formation (ref. 23).

Composition

During the past 6 years, it has become well accepted that above some altitude near 105 kilometers, atmospheric constituents are distributed in the gravitational field according to a diffusive-equilibrium law. However, several reservations must be made concerning certain constituents, and even for those constituents for which no reservation need be made concerning the diffusion equilibrium, there is doubt as to the relative concentrations at some reference altitude (any reference altitude, as indicated below).

When diffusive equilibrium prevails, each constituent is distributed as if the other were not present. For any given temperature distribution, the relative vertical distribution of each atmospheric constituent can be calculated, but the concentration of each constituent must be known at some altitude in the diffusion-equilibrium region in order that the distribution can be placed on an absolute scale. This latter requirement is a difficult one to meet. In the case of atomic oxygen, which arises in the upper atmosphere through the photodissociation of molecular oxygen, the degree of oxygen dissociation is not sufficiently well known. The relative proportions of oxygen and nitrogen, though well known in the lower atmosphere, are brought into doubt in the upper atmosphere by the oxygen-dissociation process. Consequently, the common practice has been to make an educated guess at the relative atmospheric composition at some altitude in the range 105 to 160 kilometers, and to calculate the composition through the remainder of the atmosphere on the basis of diffusive equilibrium (refs. 24–27).

During the past 6 years, two light gases have been recognized as being of dominant importance at extreme altitudes. The first of these, atomic hydrogen, was recognized as an important constituent, and its concentration established (ref. 28), on the basis of nighttime Lyman-alpha observations made in rockets above 100 kilometers (ref. 29). The atomic hydrogen arises in the chemosphere through photodissociation of water vapor and methane (ref. 30). Hydrogen has a low mass, so its concentration decreases slowly with height in the diffusive-equilibrium region, and it makes an extensive geocorona, or telluric hydrogen corona, around the Earth. Further, the highest velocity particles of such a light gas exceed the escape velocity, so there is a continuous flux of particles escaping to space of between 10^7 and 10^8 atoms/cm^2/sec. The escape of the most energetic particles appreciably modifies the distribution of the gas in the exosphere from that which would exist in the absence of escape (refs. 31 and 32). The presence of neutral hydrogen in interplanetary space can be inferred from measurements made by Morton and Purcell (ref. 33). Using an atomic-hydrogen filter, they were able to exclude from a Lyman-alpha detector, on the basis of line width, those radiations originating in a telluric corona, leaving only the Doppler-shifted radiation from interplanetary hydrogen. The interplanetary contribution to the nighttime Lyman-alpha flux at the top of the ionospheric E-region, which amounts to about 15 percent, can be accounted for on the basis of resonance scattering of solar Lyman-alpha radiation by about 0.03 atom/cm^3 in interplanetary space (ref. 34).

The second light constituent of the atmosphere now recognized as dominant in some regions of the upper atmosphere is helium. Its importance was overlooked until brought forcibly into view by Echo I drag data, which showed that time variations in atmospheric density increased in a relative sense with altitude, as expected, but only up to a point. Figure 5 (ref. 35) shows that the ratio of satellite acceleration to its average acceleration increased with altitude during the magnetic disturbances on November 12 and 15, 1960, up to 650 kilometers, but that the ratio for the Echo I satellite at 1100 kilometers was smaller than would be expected from this trend. Since the satellite acceleration depends upon atmospheric drag, these curves show that the relative magnitude of atmospheric-density variations increased with altitude up to 650 kilometers, but that the relative magnitude decreased at higher altitudes. Nicolet (ref. 36) recognized that the data in figure 5 showed that a constituent of the at-

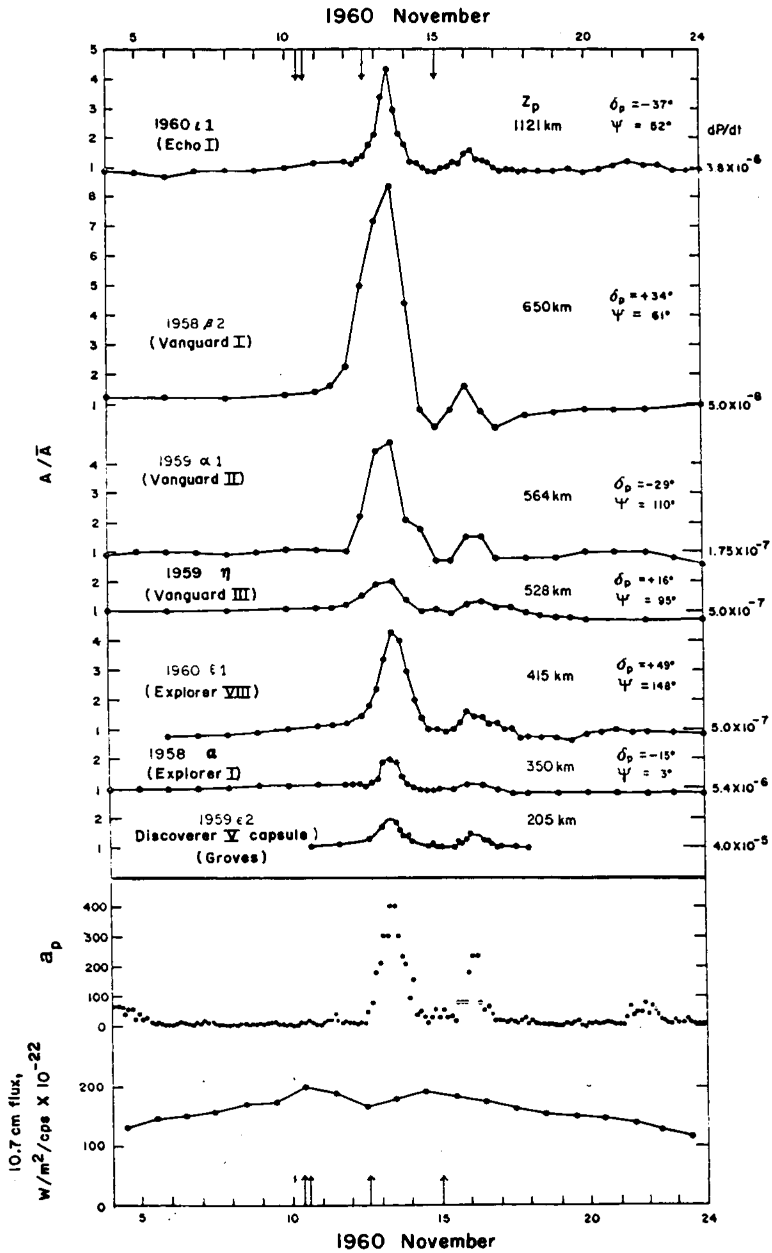

Figure 5.—Rates of orbital decay of seven artificial satellites during the November 1960 events, compared with the geomagnetic a_p index and the solar radio-noise flux (ref. 35).

mosphere lighter than atomic oxygen was predominant at 1100 kilometers, and he identified this constituent as helium. He also recognized that the neutral helium should be accompanied by ionized helium that would be important in considerations of ionospheric structure—something that Hanson (ref. 37) independently recognized in the experimental ionospheric observations made by Hale (ref. 38). Since the amount of helium in the lower atmosphere is well known, the concentration in the upper atmosphere can easily be calculated if it is known up to what altitude mixing prevails, and above which diffusion equilibrium prevails. On this basis, the data in figure 5 provide strong evidence that the altitude above which diffusion equilibrium prevails is in the neighborhood of 105 to 110 kilometers.

Hydrogen, because it is lighter than helium, predominates over helium above some altitude, so helium is the predominant atmospheric constituent only between certain altitude limits. However, these limits vary markedly with the atmospheric temperature, and hence with the sunspot cycle. Near sunspot maximum, helium predominates between roughly 1400 and 5000 kilometers. Near sunspot minimum, the region is much narrower, perhaps 500 to 600 kilometers; in fact, it may even disappear entirely. The hydrogen concentrations are thought to vary markedly in the opposite sense to the concentrations of other atmospheric constituents, increasing near sunspot minimum (refs. 39 and 40). This is believed to result from the source of atomic hydrogen being nearly constant through a sunspot cycle, while the rate of escape varies markedly, being much more rapid at the high temperatures that prevail near sunspot maximum. The source is nearly constant, because the solar radiation responsible for the photodissociation of water vapor and methane ($\lambda \approx 1800$ Å) is not significantly variable during the course of a sunspot cycle. The hydrogen concentrations therefore are controlled by the rate of escape, which is controlled by the daytime temperature. The flow of hydrogen around the Earth is sufficiently rapid so that the nighttime concentrations are also largely controlled by the daytime temperature (ref. 41). Donahue and McAfee (ref. 42) have drawn attention to the extreme complexity of a rigorous treatment of the problem of hydrogen flow around the Earth, and they have presented calculations that indicate that the diurnal variation in hydrogen concentration is substantial; as much as threefold for some temperature conditions.

Thermal diffusion acts to increase the concentration of the light atmospheric constituents, hydrogen and helium, in the warm region of the atmosphere relative to the cold. Thus the effect of thermal diffusion is to increase the concentrations of hydrogen and helium in the exosphere above those that would occur in the case of diffusion equilibrium with no thermal diffusion (ref. 40).

A reservation that must be made with regard to diffusion-equilibrium distributions is that they apply only if there is no flow of one constituent relative to another. As long as the flow is sufficiently small, the diffusion-equilibrium distributions will not be significantly disturbed. However, Bates and Patterson (ref. 43) and Kocharts and Nicolet (ref. 40) have shown that the flow of atomic hydrogen upward in the atmosphere is so rapid that its distribution departs markedly from the diffusion-equilibrium distribution. Below 200 kilometers, the atomic-hydrogen distribution for temperatures above 1250° K closely parallels that of the total atmospheric concentration, not because of mixing but because of the character of vertical diffusive flow through an atmosphere whose total particle concentration varies with altitude. The possibility that the helium distribution is disturbed by diffusive flow has been examined by Bates and McDowell (ref. 44). They find that the probable flow would disturb the equilibrium distribution only to a trivial degree.

The oxygen distribution is also disturbed by diffusive flow. Molecular oxygen is dissociated mainly at altitudes above 100 kilometers, but the recombination occurs mainly at altitudes below 85 kilometers, where the density is sufficiently high for the three-body recombination process, $O+O+M \rightarrow O_2+M$, to proceed at the required rate. Significant numbers of dissociation events occur even at altitudes above 120 kilometers. To maintain the steady-state oxygen abundances, there must be a steady upward flow of molecular oxygen and downward flow of atomic oxygen. The necessary flow significantly disturbs the diffusion-equilibrium distribution below 130 kilometers (W. B. Hanson and F. D. Colegrove, private communication). At altitudes below 110 kilometers, eddy diffusion must be taken into account in addition to molecular diffusion, as eddy diffusion is required to maintain the molecular- and atomic-oxygen distributions (especially the atomic) in the observed forms. Johnson and Wilkins (ref. 45) have shown that the thermal-energy input into the lower thermosphere limits the eddy diffusivity to lower values than those obtained from vapor- or meteor-trail analysis, the acceptable value being in the vicinity of 10^6 atoms/cm^2/sec. This value of the diffusivity appears to be at least approximately in agreement with the requirements for oxygen transport in the atmosphere.

The helium concentration in the atmosphere is less than would be expected on the basis of the release rates from the Earth's crust if no escape took place. However, the exospheric temperature near sunspot maximum is high enough to make the escape important and probably in balance, on the average, with the input, which is believed to be in the neighborhood of 10^6 atoms/cm^2/sec (refs. 44 and 40). However, if the escape of He^4 is this rapid, then there is a problem with regard to the atmospheric concentration of He^3, whose input rate into the atmosphere, calculated on the basis of nuclear reactions between cosmic radiation and atmospheric particles, is about 2 atoms/cm^2/

sec. Taking also into account the input rate of He^3 from solar-flare cosmic-radiation events, the average input rate is probably 10 atoms/cm^2/sec. Owing to its lesser mass, He^3 should escape from the atmosphere much more readily than does He^4, and, accepting the rate of He^4 escape, the computed escape rate for He^3 greatly exceeds the input rate. If, instead, the average escape rate for He^3 is low enough to agree with the input rate into the atmosphere, then He^4 would not escape as rapidly as it is released, and it should be accumulating in the atmosphere, unless some other mechanism comes into play to remove it. The computed rates of escape, averaged over the past solar cycle, are 4 He^3 atoms/cm^2/sec and 6×10^4 He^4 atoms/cm^2/sec (ref. 46). Thus, the great disparity between He^3 and He^4 escape rates, although qualitatively in agreement only with the thermal-escape hypothesis, is not in quantitative agreement with the hypothesis. The resolution of this problem is not clear.

A minor atmospheric constituent of some importance is nitric oxide. It is generally accepted that the upper and largest portion of the D-region is caused by the ionization of nitric oxide by solar Lyman-alpha radiation. The concentration of nitric oxide required to produce the D-region is very small, being of the order of 10^4 atoms/cm^3 at 85 kilometers (ref. 2). However, a recent measurement of resonance fluorescence of nitric oxide in the gamma bands at 2155 Å shows that the column density of nitric oxide above 85 kilometers is 1.7×10^{14} molecules/cm^2 (ref. 47), corresponding to a concentration at 85 kilometers of about 10^8 molecules/cm^3. This gives rise to a new problem—why the D-region behaves as it does, if the nitric-oxide concentrations are as large as indicated by the fluorescence measurements. The source of nitric oxide must lie in the chemical reactions of the chemosphere (ref. 2). Even with the surprisingly large concentrations indicated by the fluorescence measurements, nitric oxide is still a very minor constituent of the atmosphere. Since the total concentration of atmospheric particles above 85 kilometers is about 10^{20} particles/cm^2, nitric oxide amounts to about 2 parts per million.

To determine the concentrations of the major atmospheric constituents at high altitudes, and to test the diffusion theory for their distributions, measurements of the neutral constituents are needed above 100 kilometers. Mass-spectrometer measurements in rockets have been made by Schaeffer (ref. 48) and Nier et al. (ref. 49), and are in reasonable agreement with the results of the diffusion theory. However, more critical tests are required, and satellite data are needed to give the global pattern of upper atmospheric composition.

Figures 6 through 8 show atmospheric-concentration data as a function of altitude for three widely differing conditions of solar activity (ref. 45). Figure 6 applies to nighttime conditions near sunspot minimum, with an exospheric temperature near 700° K, and with atomic-hydrogen concentrations corresponding to a temperature of 930° K, which is the expected daytime temperature. Figure 7 applies to daytime conditions near sunspot maximum, with an exospheric temperature of 1800° K. Figure 8 applies to daytime conditions for an intermediate situation, with an exospheric temperature of 1300° K. The concentrations shown here, combined with the 1300°-K temperature profile shown in figure 1, produce an atmosphere whose density is close to that adopted for the U.S. Standard Atmosphere, 1962, but the composition structure is physically more realistic than the Standard Atmosphere.

Density

The vertical profile of atmospheric density is controlled by the temperature and composition profiles. However, the most detailed observations of the upper atmosphere are of density rather than temperature or composition;

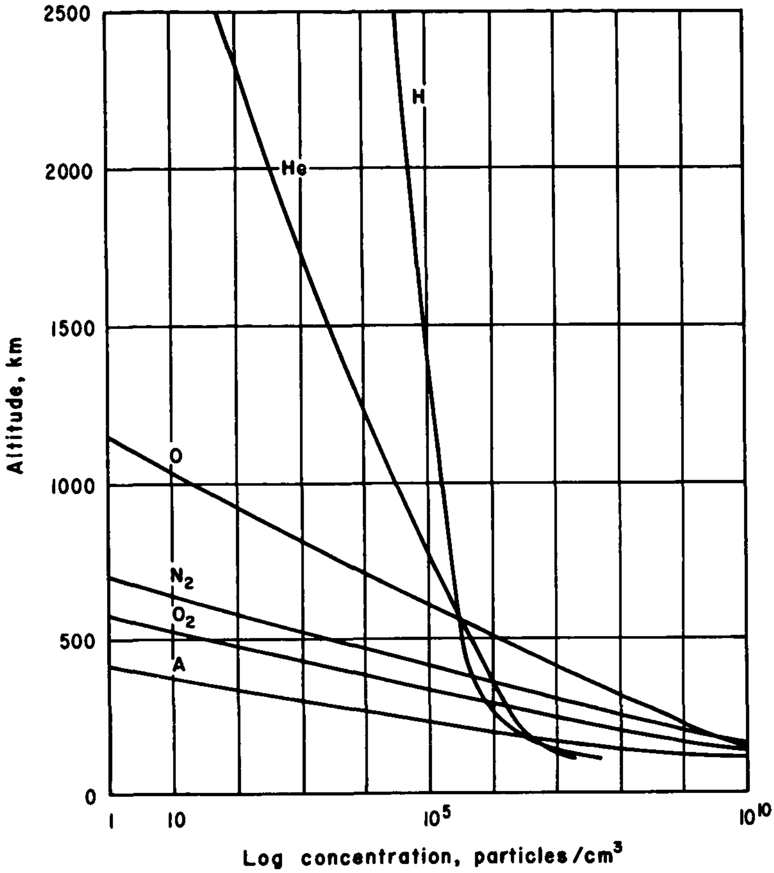

Figure 6.—Concentration of atmospheric constituents during the nighttime near sunspot minimum, with exospheric temperature 700° K.

the density data are obtained mainly from the rates of decay of satellite orbits. It is not possible to use the density data to derive uniquely the temperature and composition profiles. It is necessary to make explicit assumptions regarding the composition and, to a lesser extent, the general shape of the temperature profile. The temperature profile above 100 kilometers is believed to be controlled mainly by heat conduction downward (refs. 24 and 50), and this concept makes possible the introduction of profiles thought to be realistic. By these means, density data can

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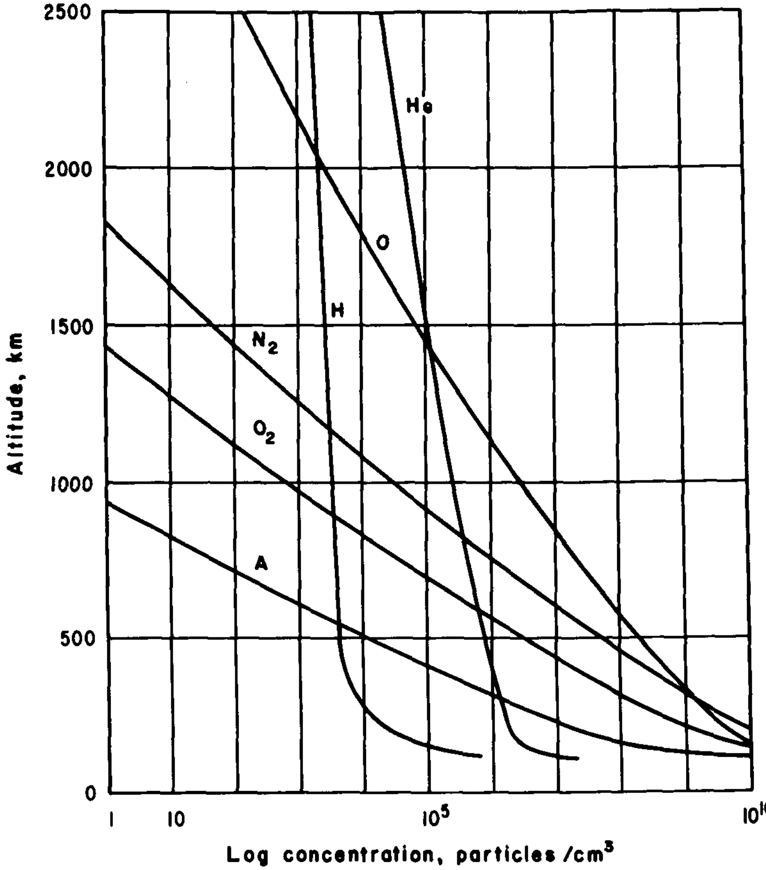

Figure 7.—Concentration of atmospheric constituents during the daytime near sunspot maximum, with exospheric temperature 1800° K.

be converted to temperature, and the agreement among different research groups working independently is generally better than 10 percent (ref. 6).

The general pattern of density variations in the upper atmosphere is similar to that of temperature, but the amplitudes are much greater. For example, when the exospheric temperature changes from 700° to 1800° K, the density at 500 kilometers increases by a factor of over 100. The variation of density with altitude is shown in

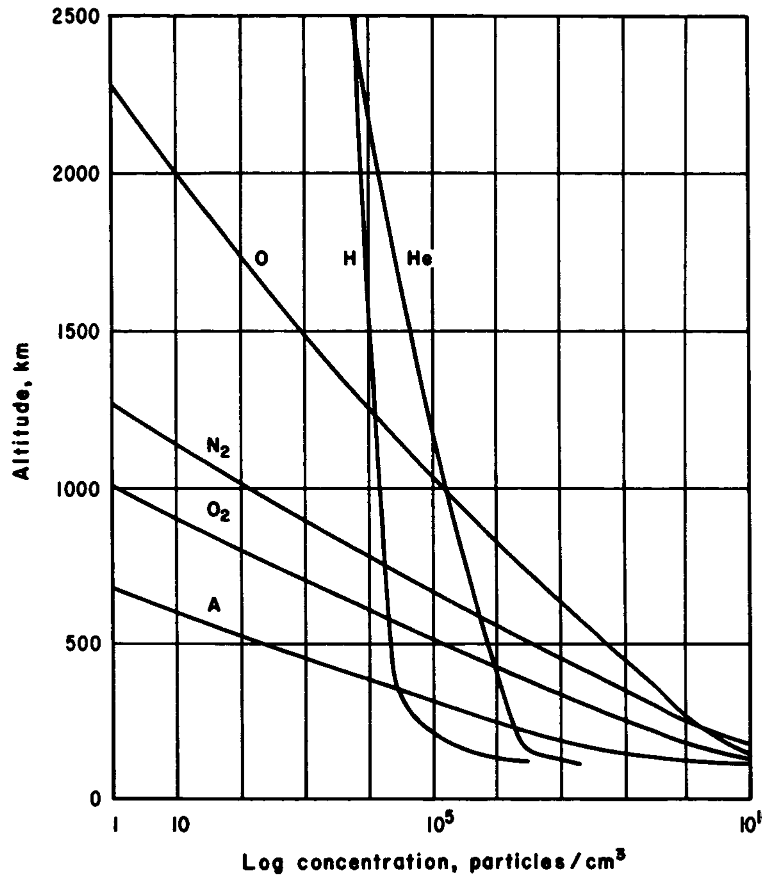

Figure 8.—Concentration of atmospheric constituents with an exospheric temperature of 1300° K.

figure 9 for three exospheric temperatures. Atmospheric densities above 300 kilometers only occasionally fall outside the limits indicated by the extreme curves in figure 9, while the intermediate curve is the density distribution adopted for the U.S. Standard Atmosphere, 1962.

When satellites were first launched, the rates of orbital decay were much more rapid than had been anticipated, indicating atmospheric density at satellite altitudes greater than that predicted on the basis of earlier data. The nature of the error in prediction is somewhat different

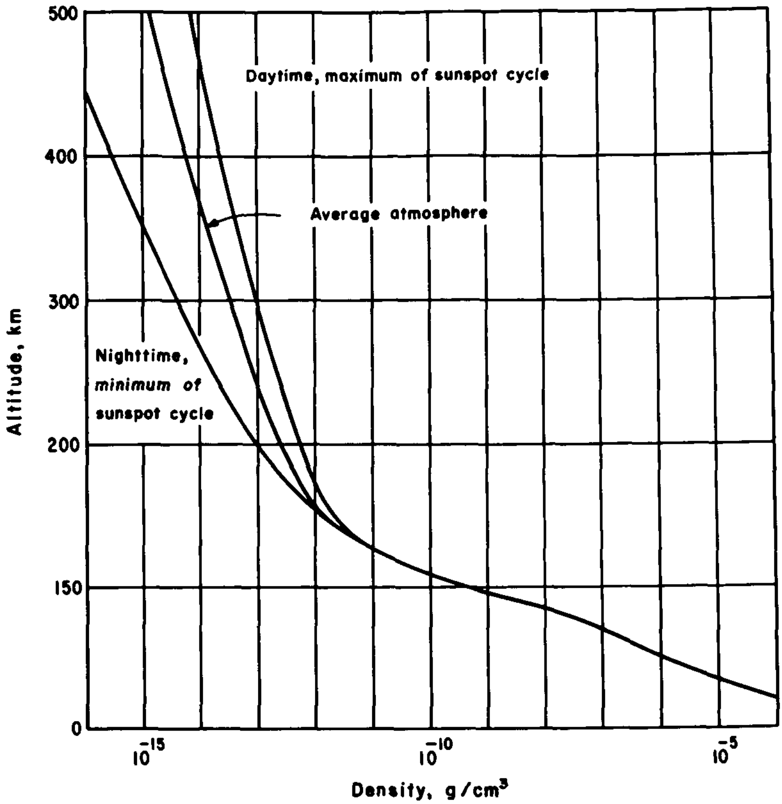

Figure 9.—Variation of atmospheric density with altitude for three exospheric temperatures.

from what was originally assumed. Atmospheric-density predictions prior to satellite flight were based mainly on data characteristic of sunspot-minimum conditions, and models were sometimes specifically restricted as applying to such conditions (ref. 24). The fact that the early satellites, flown near sunspot maximum, encountered densities larger than predicted reflects the fact that the very large variation with sunspot cycle was not fully anticipated. Recent data are characteristic of sunspot minimum, and are in close agreement with the presatellite predictions.

Atmospheric Motion

In the lower thermosphere, strong wind shears have been observed, originally in long-persisting meteor trails (ref. 51) and, more recently, mainly in trails formed by vapor releases from rockets (refs. 52 and 53). The shear zones are frequently associated with reversals in the wind that tend to occur with spacings of a few kilometers. For a long time, these reversals were rather mysterious occurrences, since it did not seem conceivable that the thermal structure of the atmosphere could produce such patterns in the gradient or geostrophic wind. Two examples of the wind reversals are shown in figure 10 (ref. 54).

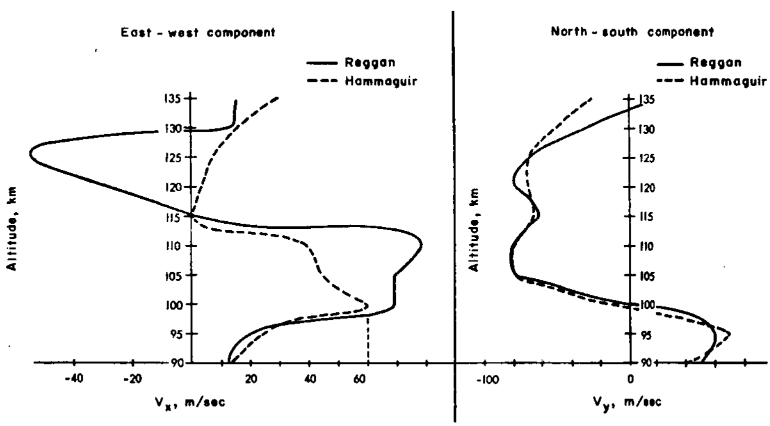

***Figure 10.*—Simultaneous measurement of windspeed at two sites (Reggan, 26° N, 5° E; and Hammaguir, 30° N, 3° W) 900 kilometers apart (ref. 54).**

These are simultaneous measurements made at two stations separated by 900 kilometers.

The most important development during the past 6 years concerning motion of the upper atmosphere has been the recognition that the wind reversals in the lower thermosphere are due to internal gravity waves (ref. 55). No other mechanism has been suggested as a possible cause for the strong shear zones that are observed in the lower thermosphere.

An internal gravity wave is a wave in which the group velocity propagates almost vertically upward while the phase velocity is downward, and the individual particle motions are nearly horizontal. The small vertical component of the particle motion is sufficient for gravity to provide the restoring force for the wave motion. The waves are thought to originate in the troposphere, either near the Earth's surface or near the jetstream. Owing to the decrease in atmospheric density with altitude, the wave amplitude must increase with altitude if the energy flux is to remain constant with altitude. Thus, the large-amplitude waves observed in the lower thermosphere are entirely consistent with the lack of observable or identifiable waves in the troposphere; they are simply too small to identify in the troposphere. The horizontal extent of the wave motion is of the order of 1000 kilometers, as can be seen from figure 10 (ref. 54), and the periods are of the order of 100 minutes.

As internal gravity waves move upward in the thermosphere into regions where the mean free path of the atmospheric particles become significant in comparison with the wavelength, viscous damping becomes important (ref. 56), and the wave energy becomes dissipated as heat. The resulting energy input may contribute in an important degree to the energy budget of the middle and upper thermosphere (roughly, the region above 140 kilometers). However, this point has not been established beyond reasonable doubt.

Another probable important consequence of internal gravity waves is the production of eddy mixing in the lower thermosphere. The lower thermosphere, and even the mesosphere, is thermodynamically stable, and a mechanical driving force is required to produce any eddy mixing that occurs, since work must be done against buoyancy forces in order to accomplish the eddy mixing. A constant shear with altitude, which could be produced by an appropriate (though unrealistic) thermal structure, could provide the driving force, but such a circulation pattern is not in agreement with the wind observations that have been made. A more plausible possibility is that mixing at a given altitude proceeds sporadically as the strong shear zones associated with internal gravity waves pass through that altitude region.

Internal gravity waves also provide an explanation for the occurrence of sporatic E-layers in the ionosphere. When the shear zone associated with an internal gravity wave is appropriately oriented relative to the magnetic field, a layer of enhanced ionization can be produced (ref. 57) similar to the sporadic-E electron-concentration profile observed in rockets (ref. 58). Other ionospheric perturbations have been observed that appear to be caused by internal gravity waves. It appears that evidence from ionosonde data may provide some of the best information on internal gravity waves. Knudsen and Sharp (ref. 59) have observed repeated reversals in the profile of ion temperature in the E-region; these also have the appearance of being caused by internal gravity waves.

Atmospheric tides have long been known to be of relatively large amplitudes at ionospheric altitudes, because of the magnitude of the magnetic variations they cause. The lunar tidal oscillations of atmospheric pressure observed at the ground are thought to be entirely due to gravitational forces, whereas the solar tidal oscillations are believed to be mainly due to solar heating. Previous theories of resonant, gravitational excitation of the solar tidal oscillations are not consistent with the patterns of atmospheric structure obtained from rocket measurements (ref. 60.) This, again, suggests that thermal excitation must predominate.

Large-scale circulation of the upper atmosphere is to be expected as a consequence of the nonuniform heat input into the thermosphere (ref. 61). However, the heat inputs from different sources remain so uncertain that one cannot state with confidence just what the average large-scale circulation should be, or how much the pattern might deviate from the average on a day-to-day basis. Vapor-trail observations have provided much useful information, and they indicate an equatorward component for the motion above 150 kilometers (M. Dubin, private communication). If this is an accurate generalization, it may be inferred that polar heat sources in the middle thermosphere (either energetic particles or hydromagnetic waves) exceed in average intensity the solar ultraviolet and all other heat inputs into the middle thermosphere at low and middle latitudes. However, doubt remains on this point.

It was mentioned above that the composition of the thermosphere is affected by the eddy transport of molecular and atomic constituents of the atmosphere. Large-scale circulation also affects composition, but in a different way than eddy mixing does, since the effect of upward or downward motion in the lower thermosphere is concentrated in particular geographic regions. In eddy transport, upward and downward motions occur in a random pattern over the entire geographic region involved. On this account, global measurements of atmospheric composition should contain the information required to identify regions in which there is a vertical component of motion in the lower thermosphere. The information applies to the lower thermosphere, because the lower thermosphere contains the mechanisms that control atmospheric composition at higher altitudes, and the atmosphere is always well mixed up to the mesopause.

Airglow

One interesting airglow emission is Lyman-alpha radiation from atomic hydrogen. A nighttime flux of Lyman-alpha radiation incident upon the upper atmosphere was first observed by Kupperian et al. (ref. 29). This was interpreted by Johnson and Fish (ref. 28), on the basis of the lack of any Doppler shift, as radiation originating in a telluric hydrogen corona through resonance scattering of sunlight. This interpretation was largely confirmed when the telluric absorption line was observed in the solar Lyman-alpha radiation incident upon the lower thermosphere (ref. 62). However, Donahue and Thomas (ref. 63) showed that some quantitative difficulties remained in the complex radiative-transfer problem. These related to the amount of hydrogen in the geocorona, in interplanetary space, or in a cloud moving with the Earth but too far removed from it to be gravitationally bound. Morton and Purcell (ref. 33) introduced a powerful new experimental technique when they placed an atomic-hydrogen filter cell in front of their detector to eliminate the radiation scattered by the telluric hydrogen corona. In this way, they showed that about 15 percent of the incident radiation was of extraterrestrial origin. Patterson, Johnson, and Hanson (ref. 34) identified this extraterrestrial source as resonance scattering of sunlight by interplanetary hydrogen, and calculated the concentration of hydrogen in space. They found that the required concentration beyond the orbit of Jupiter was 0.03 atom/cm^3. Further observations of the type originated by Morton and Purcell can be expected to be a powerful tool for studying interplanetary hydrogen, since the Doppler shift can be used to determine the velocity of the source atoms.

Dayglow has proved difficult to measure from rockets or space vehicles, because of the stray-light problem, but this has been overcome during the past several years. Fastie et al. (ref. 64) used a rocket-borne spectrophotometer to obtain the intensity-versus-altitude profile for resonance scattering by atomic hydrogen at 1216 Å, atomic oxygen at 1304 and 1356 Å, and atomic nitrogen at 1200 Å. Zipf and Fastie (ref. 65) have observed the emission-versus-altitude profile for N_2^+ at 3914 Å. The resonance scattering of nitric oxide in the gamma bands at 2155 Å has been observed by Barth (ref. 47). The intensity-versus-altitude profile for hydrogen Lyman-alpha radiation showed a steady but slow decrease, as would be expected on the basis of scattering in a geocorona. The intensity-versus-altitude profile for the oxygen-resonance lines at 1304 Å showed no corresponding decrease with altitude, but, instead, showed a broad maximum near 180 kilometers. The observed decrease in intensity above 180 kilometers is surprising, in view of the large optical depth for oxygen-resonance radiation, which should result in trapping of the oxygen radiation by multiple scattering. Fastie and Crosswhite (ref. 66) have repeated the experiment, and confirmed the decrease in intensity with altitude above 180 kilometers.

Nightglow is easier than dayglow to measure from rockets, because of the lesser stray-light problem. Several useful observations have been made during the past 6 years, the most interesting probably being that of Lyman-alpha emission (refs. 64 and 33).

For a long time, it was assumed that the oxygen green-line (5577 Å) emission was excited by the Chapman (ref. 67) mechanism

$$\mathrm{O}+\mathrm{O}+\mathrm{O}\rightarrow \mathrm{O}_2+\mathrm{O}(^1S)$$
$$\mathrm{O}(^1S)\rightarrow \mathrm{O}(^1D)+h\nu(5577\ \text{Å})$$

However, Barth and Hildebrandt (ref. 68) and Young and Clark (ref. 69) have measured the rate coefficient for this reaction and found it entirely inadequate to produce the observed green-line intensity. A two-step process has been proposed instead (ref. 70)

$$\mathrm{O}+\mathrm{O}+\mathrm{M}\rightarrow \mathrm{O}_2^*+\mathrm{M}$$
$$\mathrm{O}_2^*+\mathrm{O}(^1D)\rightarrow \mathrm{O}(^1S)$$
$$\mathrm{O}(^1S)\rightarrow \mathrm{O}(^1D)+h\nu(5577\ \text{Å})$$

The equatorial red arc is due to the oxygen red line (6300 Å), and it has been shown to correlate well with the electron concentration at the F_2 peak of the ionosphere (ref. 71). This suggests that an ion-recombination mechanism is responsible, at least part of the time. In other cases, it is felt that elevated electron temperature may be responsible, particularly in the midlatitude or subauroral red arcs.

Fastie et al. (ref. 72) have obtained an ultraviolet spectrum of an auroral cloud. Neither hydrogen Lyman-alpha radiation nor nitric oxide bands were observed, but strong emissions were observed from the second positive spectrum of N_2, the Vegard-Kaplan bands of N_2, and the ground-state lines of atomic oxygen.

The ratio of hydrogen-alpha emissions to molecular-nitrogen-ion emissions in auroras shows that protons cannot provide the principal energy input for bright and distinct auroral features (ref. 73). This observation has been confirmed by rocket measurements (refs. 74 and 75) which revealed that electrons constitute the principal energy source in bright auroral features. Satellite observations have shown that the auroral electrons have a softer spectrum than Van Allen electrons (refs. 75 and 76). The energy dissipated in auroras in an hour is large compared to the energy of the Van Allen radiation belt, so it now appears more likely that the Van Allen radiation (at least at high latitudes) is a byproduct of the auroral phenomenon rather than vice versa (ref. 76). The N_2^+ emission at 3914 Å has been identified as a valuable index of energy input into auroras by ionizing radiation, because excitation arises only at the time of ionization of the nitrogen molecule, and about 2 percent of the ionizing events lead to the emission of 3914-Å photons (ref. 77).

Auroral electrojets are strong ionospheric-current systems that occur in the auroral zone. Although their cause is not entirely clear, it now appears probable that they are a byproduct of the radiation belt (ref. 78). The geomagnetic field is deformed by the solar wind, and as the Earth rotates, the deformation continues to be directed away from the Sun. The trapped radiation as it progresses around the Earth moves closer to the Earth on the side away from the Sun, as a consequence of the conservation of the integral invariant. The trapped radiation, which is mainly protons, is neutralized electrically by a thermal plasma with an excess of electrons. As the Earth rotates, the thermal plasma moves in and out in the same sense as the magnetic field; as this motion is out of phase with the movement in and out of the trapped radiation, a charge separation is produced. The resulting potential field drives Hall currents in the ionosphere, and these are the auroral electrojets.

METEOROIDS

The flux of micrometeoroids in space is highly variable and difficult to determine. The quantitative effect of meteoroid impact, either on the atmosphere or on a detector, is not well known, because particles cannot be satisfactorily accelerated in the laboratory to meteoric velocities for calibration purposes. Much data had been collected, but the interpretation has been sharply revised from time to time. A zero-magnitude meteor moving with a velocity of 30 km/sec has been attributed to particles varying in mass from 0.01 gram (ref. 79) to 25 grams (ref. 80), with the presently accepted figure lying near 1 gram (ref. 81). The density of meteoroids remains in doubt. Photographic studies of meteor trails provide evidence for a loosely bound meteoroid structure with density near 0.01 g/cm^3. The micrometeoroids may not consist of such loose, fluffy structures, in which case a density greater than unity would probably occur.

Direct measurements of micrometeoroid impact on space vehicles have been made with microphones (refs. 82 and 83), wire grids (ref. 84), light-flash impact detectors (ref. 85), pressurized chambers (refs. 86 and 87), and specially prepared collecting surfaces (ref. 88). Figure 11 (ref. 89) summarizes many of the results. It shows the substantial differences among the various ob-

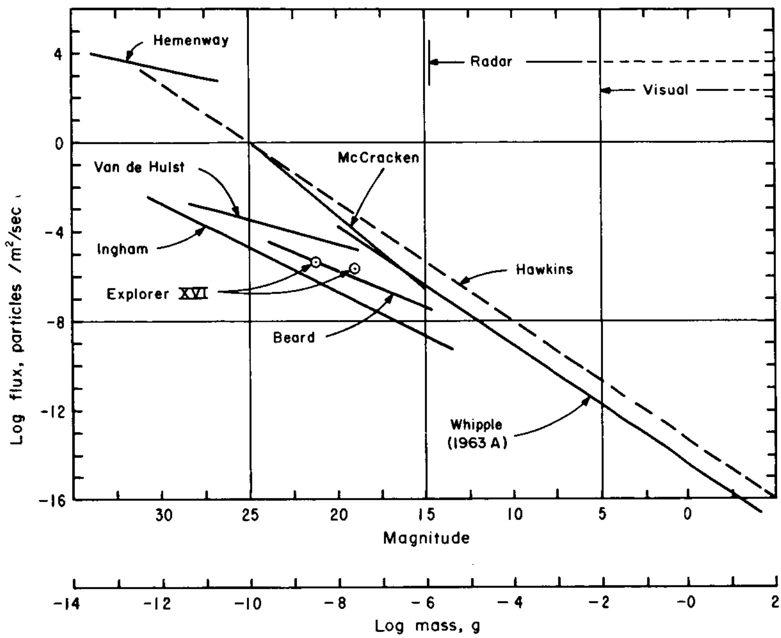

Figure 11.—Cumulative fluxes near Earth of micrometeoroids with masses greater than a given mass or magnitudes less than a given magnitude (ref. 89).

servations and shows the substantial reduction with increasing mass in the number of expected impacts.

Even if the micrometeoroid-flux rates were known accurately, it would not be possible to state the penetration hazard, since the penetration properties of the high-speed meteoroid material are not known. The direct penetration data that have been obtained (ref. 87) are therefore especially valuable in this connection. Figure 12 (ref. 81) presents the best estimate presently available for penetration of aluminum sheets; the penetration times for steel would be about 10 times longer.

An appreciable concentration of micrometeoroid material in the vicinity of the Earth has been observed (ref. 90), apparently due to the effect of the Earth's gravitational field. This effect is shown in figure 13, which indicates a decrease by a factor of 100 000 in the micrometeoroid

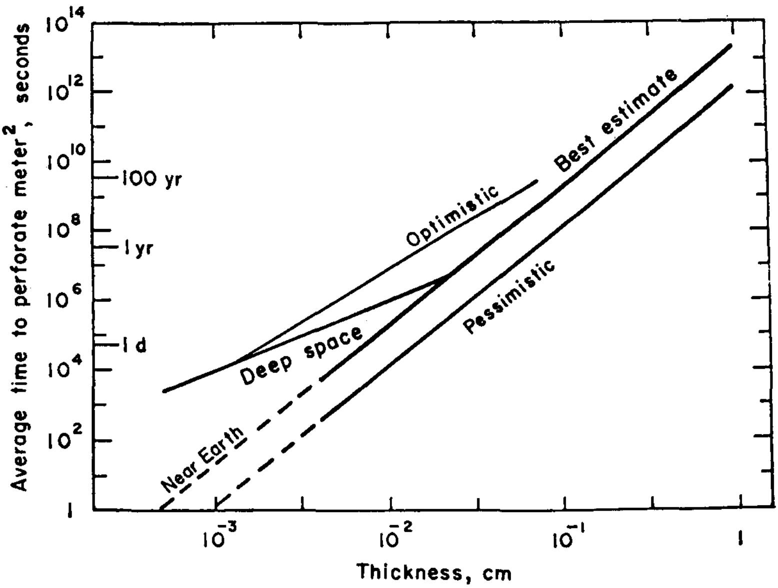

Figure 12.—Average time for perforation of aluminum skin by meteoroid penetration (ref. 81). Times for steel should be about 10 times longer.

flux in interplanetary space compared to that near the Earth. The effect is also indicated in figure 12 by the different estimates for near-Earth and deep-space conditions, which indicate that the enhancement of the dust cloud near the Earth disappears for particles heavier than 10^{-6} gram.

Meteoroid showers have also contributed to the variability of meteoroid-flux observations made in space vehicles. For example, Alexander et al. (ref. 91) observed an enhanced micrometeoroid flux associated with the Leonid meteoroid stream. However, many of the older meteoroid streams that are detected visually or by radar do not contain significant numbers of micrometeoroids, presumably because they have been dispersed from the stream by the Poynting-Robertson effect, light pressure, or solar-wind bombardment.

Meteoroids in space scatter sunlight and thus produce zodiacal light. Within the uncertainty produced by such

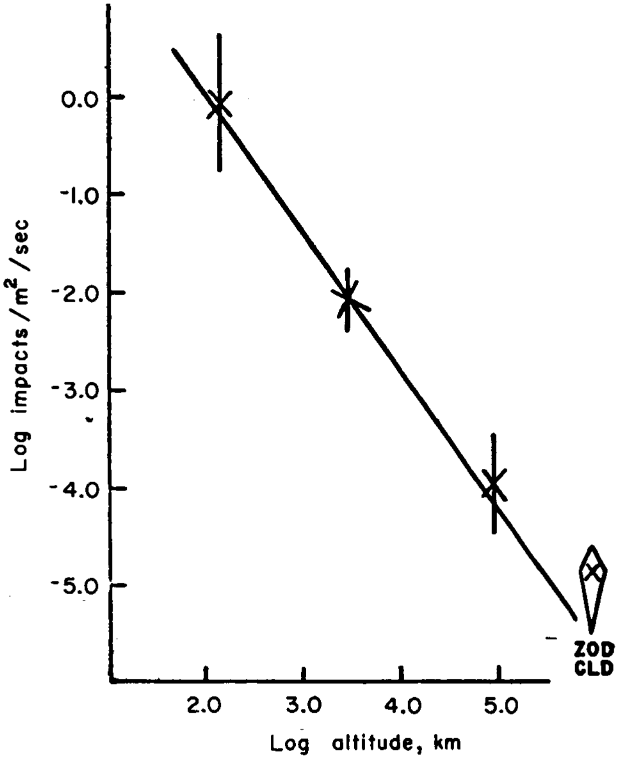

Figure 13.—Variation with altitude above the Earth's surface in the flux of micrometeoroids (ref. 90). ZOD CLD indicates the flux of dust particles that constitute the zodiacal cloud in interplanetary space.

poorly known parameters as meteoroid density, the intensity of the zodiacal light can all be attributed to the scattering of sunlight by micrometeoroids in interplanetary space. At one time, a portion of the zodiacal light was attributed to electrons in interplanetary space (ref. 92). However, later observations showed no polarized component that had to be attributed to electrons (ref. 93). Any electron contribution to the zodiacal light has the Fraunhofer structure smeared out, owing to the high thermal velocity of electrons, whereas dust particles provide a scattered-light spectrum that includes the Fraunhofer structure. Making use of this circumstance, Beggs et al. (ref. 94) have evaluated the electron contribution as between 1 and 2 percent of the total arising from about 16 electrons/cm^3 in interplanetary space.

Noctilucent clouds have been observed frequently at altitudes near 80 kilometers at high latitudes in summer. It was often speculated that these might be due to meteoric dust (ref. 95), although other arguments supported the concept that they consisted of ice crystals (ref. 23). Rocket experiments have succeeded in capturing cloud particles on sensitized surfaces (ref. 96). These showed the presence of solid particles, but the impacts also showed evidence that the particles might have been encased in ice. A later flight, which did not pass through a recognizable cloud, recorded particles without any evidence of ice, but in substantially lower numbers. Hence, it is reasonable to assume that noctilucent clouds owe their visibility to the presence of ice, and that the ice crystals form on dust particles of meteoric origin. However, a problem remains in the variability of the number of dust nuclei.

MARS

On the basis of optical scattering data, it has been believed in the past that the surface pressure on Mars is about 85 millibars (refs. 97 and 98). However, the optical-scattering technique, including polarization, for the determination of surface pressure is not a very accurate one, as the scattering by small particles that are apt to be present in the atmosphere cannot be evaluated. The surface pressure tends to be overestimated, even by as much as an order of magnitude (ref. 99). The presence on Mars of a blue haze is suggestive that small particles are present, and that the surface-pressure value of 85 millibars is therefore an overestimate.

A more reliable technique for the determination of the surface pressure involves the pressure broadening of lines in the band spectrum of CO_2. Two lines with different pressure-broadening characteristics are required, one essentially to evaluate the amount of CO_2 present in the atmosphere and the other to determine the pressure to which it is subjected. Kaplan et al. (ref. 100), utilizing this technique, find a surface pressure 25 ± 15 millibars and a CO_2 content 55 ± 20 m-atm. They also find that the O_2 content does not exceed 70 cm-atm.

Infrared-spectral measurements made from Stratoscope II (ref. 101) indicate a higher surface pressure, about 145 millibars (ref. 100). However, it is probable that this result is in error, perhaps owing to an error in the determination of the solar-spectrum background. Kuiper (ref. 99) concludes that a surface pressure between 10 and 20 millibars is likely.

Kaplan et al. (ref. 100), using spectral plates that they made during the 1962 opposition, identified water-vapor lines at 8176.97, 8189.27, and 8226.96 Å. From these, they evaluated the water-vapor content of the Martian atmosphere as 14 ± 7 μ, in good agreement with Sagan's (ref. 102) estimate of 10 μ, based on the temperature of the polar caps, assuming that they were subliming.

VENUS

Six years ago, the surface temperature of Venus was most often thought to be no more than modestly in excess of the highest temperature that had been determined on the basis of infrared spectroscopy. This was about 285° K. However, it was realized that clouds or haze made any determination of the true surface temperature impossible. When microwave measurements disclosed brightness temperatures near 600° K for 10-centimeter wavelengths (ref. 103), the source of the radiation was not apparent. Three possible models were conceived to explain this, two with surface temperatures of 600° K or above, and the other with a dense, warm ionosphere that was considered

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to be the source of the microwave radiation (ref. 104). The microwave data were soon shown to indicate a surface temperature of about 700° K (ref. 105). At about the same time, Spinrad (ref. 106) showed that lines in the CO_2 spectrum showed temperatures near 440° K and pressures near 5 atmospheres. The surface conditions could be expected to be considerably more extreme. Further, the fact that Spinrad could see so deeply into the Venusian atmosphere showed that, of the two warm-surface models that had been considered, only the greenhouse hypothesis was tenable, as the thick dust clouds hypothesized in the other model (the aeolosphere model) would not have permitted the CO_2 radiation to escape.

The atmosphere of Venus is so hazy that the surface cannot be seen in visible light, and the temperature at the top of the haze layer is very low, about 235° K, according to radiometric measurements made at wavelengths near 10 μ. Until recently, water vapor had not been definitely identified (ref. 107). However, a recent balloon flight (ref. 108) has shown that the water-vapor content above the cloud tops amounts to about 2×10^{-2} g/cm^2 if the pressure at the cloud top is 90 millibars, or 5×10^{-3} g/cm^2 if the pressure is 600 millibars, these pressures covering the usual range of estimates. Still more recently, Bottema et al. (ref. 109) have shown that the haze or cloud particles have the spectral properties of ice. This may end the long series of conjectures that the particles might consist of solid carbon dioxide or some relatively exotic compound. It is interesting to note that the concentration of water vapor above the cloud tops on Venus is comparable to the amount present in the Earth's atmosphere at similar pressure levels (ref. 108).

Radar measurements have disclosed that the rotational period of Venus is very long, and that it probably rotates synchronously with its orbit around the Sun, thus always presenting the same side to the Sun (refs. 110 and 111).

However, Goldstein (ref. 117), in a recent review, concludes that the planetary rotation is retrograde, so that the Venusian day would be approximately four Earth-months in length. Under conditions of such slow rotation, either retrograde or prograde, atmospheric circulation can proceed almost totally uninhibited by the Coriolis force. Owing to the great density and heat capacity of the Venusian atmosphere, very slow currents, of the order of 1 m/sec, can transport from the sunlit to the nighttime side of the planet an amount of heat sufficient to maintain the dark side approximately as warm as the day side (ref. 113). Neither the radio data nor the infrared data show any appreciable difference in temperature between the light and dark sides (ref. 114).

The Mariner II spacecraft carried both infrared and microwave radiometers. The infrared radiometers observed the 10.4- and 8.4-μ CO_2 bands. The former is strong enough so that radiation would originate near the top of the clouds, while the latter is weak enough so that, in the absence of clouds, the radiation would come from well below the cloud level. The brightness temperatures from the two radiometers were the same, indicating continuous cloud cover. Limb darkening was observed, but as it appeared to be about the same on both channels, this was probably also caused by the cloud structure that prevailed at the time (ref. 115). The microwave radiometers operated at 13.5 and 19.0 millimeters. At the center of the disk, these indicated a brightness temperature of 570° K, and limb darkening was observed (refs. 116 and 117). Thus, the Mariner II observations confirm the high surface temperature for Venus. However, Barrett and Staelin (ref. 118) have shown that detailed problems remain with regard to the microwave emission, and it is suggested that the surface pressure is greater than 100 atmospheres, or that there is a dust concentration of the order of 10 g/m^3 in the lower atmosphere.

The reason for the very high surface temperature on Venus is not understood. It has been suggested that it is due to a greenhouse effect, but the temperature is surprisingly high for a greenhouse effect in view of the high albedo. The required greenhouse effect cannot be provided from CO_2 alone, but it is thought that water vapor in the amount 10 g/cm^2 would produce the required effect (ref. 119). The failure for a long time to detect any water on Venus was therefore a circumstance disturbing to the greenhouse theory.

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During the years 1958–1964, some new knowledge has developed concerning the atmosphere of Jupiter. Prior to 1960, the principal information was that the atmosphere contained 150 m-atm of methane and 7 m-atm of ammonia above the cloud deck that obscures the surface (ref. 120). Then Kiess et al. (ref. 121), using the very high resolution that was required, found four lines of molecular hydrogen in the photographic infrared. These were quadrupole lines, predicted more than 20 years earlier by G. Herzberg. Spinrad and Trafton (ref. 1) evaluated this observation in terms of the molecular-hydrogen content above the cloud deck and showed that it indicated about 27 km-atm. This indicated that molecular hydrogen is a major, and possibly predominant, constituent of the Jovian atmosphere. Other gases that might be present, such as helium, argon, and neon, are not easily detected or evaluated by spectroscopic means.

Spinrad (ref. 122) has made use of some data on star occultations by Jupiter to determine a probable atmospheric composition. Baum and Code (ref. 123) made the star-occultation observations and found a scale height for the Jovian atmosphere that indicated a mean molecular weight of 3.3, assuming a temperature of 86° K. While this in itself indicates a substantial hydrogen content for the atmosphere, additional information is required, and this was supplied by observations of the pressure broadening of methane lines by Spinrad and Trafton (ref. 124), who showed that the total amount of inert gas above the cloud deck is limited to about 16 km-atm. With this information, Spinrad was able to suggest the following composition for the Jovian atmosphere:

Gas	M	Percent (by number)	km-atm
CH_4	16	1	0.15
NH_3	17	.05	.007
H_2	2	60	27
He	4	36	16
Ne	20	3	.7

This mixture has a mean molecular weight of 3.4. Öpik (ref. 125) states that the mean molecular weight should be somewhat higher, about 4.3, on the basis that the temperature involved in the scale-height conversion to molecular weight should be higher than the values used by Baum and Code; Öpik used a value of 112° K. This would require increasing the neon-to-helium ratio in the above table, and would probably even permit the inclusion of some significant amount of argon.

Temperatures can be derived from the quadrupole lines of hydrogen. Zabriskie (ref. 126) found a rotational temperature of 170° K, while Spinrad (ref. 122) obtained 120° K. The difference reflects the uncertainties in the measured quadrupole-line strengths in the planetary spectra.

chapter 3

Summary and Conclusions

IN RECENT YEARS, results from sounding-rocket and satellite measurements and theoretical and laboratory research have contributed greatly to a better understanding of the Earth's atmosphere. The description of phenomena in the upper atmosphere has become more detailed, and the interpretation of the physical and chemical processes occurring has broadened to include new concepts.

A start has been made in studying the atmospheres of Mars and Venus. One of the most challenging problems of the near future will be the direct investigation of Mars and its atmosphere.

It has been learned that the isothermal-temperature distribution of the Earth's atmosphere above 300 kilometers is subject to marked variations in temperature from day to night, and to other variations that can be correlated with solar activity. There are also annual and semi-annual variations and changes with latitude. These latter are not yet well understood. In addition to these, the longest and largest single variation follows the 11-year cycle of solar activity.

Exceedingly interesting, and sometimes unexpected, details of atmospheric phenomena have been learned that will be of great importance in achieving a detailed understanding of the behavior of the atmosphere. It has been found experimentally that the temperature at high latitudes in the 80-kilometer-altitude region is considerably lower in the summer than in the winter. Also, a number of phenomena have been verified that indicate certain processes of the atmosphere are not in a state of equilibrium at all times, and that these departures from equilibrium are important in determining atmospheric behavior. For instance, the electron temperature has been found to be higher than the neutral-particle temperature in the upper regions of the daytime ionosphere, and the difference is quite large shortly after sunrise. In studying the altitude distribution of components of the upper atmosphere, it has been recognized that disturbances of diffusive-equilibrium distribution are significant in the cases of atomic hydrogen and oxygen. In the case of hydrogen, the rate of escape varies considerably over the course of a sunspot cycle, while the source is relatively constant. Accordingly, hydrogen concentrations are governed by the rate of escape, which is determined chiefly by the daytime temperature. In the case of oxygen, owing to different altitude regions in which the greater part of the dissociation and recombination processes occur, there is a steady flow upward of molecular oxygen and a downward flow of atomic oxygen in the 85- to 130-kilometer region.

The role of helium in the upper atmosphere is understood on a qualitative basis, but quantitative agreement with input and rate-of-escape hypotheses has not been reached.

Rocket measurements confirming the presence of nitric oxide in the D-region have opened a question as to the detailed processes occurring, since the measurements indicate a concentration about 10 000 times that calculated to be required to produce the D-region. The importance of minor constituents in the atmosphere is well illustrated here, for the concentration of nitric oxide amounts to about 2 parts per million at 85 kilometers, on the basis of the rocket measurements.

The most detailed observations of the upper atmosphere are of density. While the vertical profile of atmospheric density is controlled by the temperature and composition profiles, it is not possible to use density data to derive temperature and composition uniquely. Assumptions regarding composition or temperature profiles must also be made. However, different research groups, working independently in converting density data to temperature, generally agree to better than 10 percent.

Density variations in the upper atmosphere are similar to temperature variations, but much larger. Early satellites, flown near sunspot-cycle maximum, encountered densities larger than predicted. More recent satellite data, obtained during sunspot minimum, are closer to the original predictions. As a result of this research, the role of the Sun in determining upper atmospheric density is more fully understood, and our theories have been broadened to account for the effect of changing solar-energy input to the atmosphere.

Strong wind shears observed in long-persisting meteor trails and by vapor releases from rockets are now believed to be due to internal gravity waves, thought to originate in the troposphere. The roles of internal gravity waves in the energy budget of the atmosphere above about 140 kilometers, in the production of eddy mixing in the lower thermosphere, and as an explanation of sporadic E are problems that will receive detailed attention in the next few years.

Previous theories of resonant gravitational excitation of solar tidal oscillations in the atmosphere are not consistent with the emerging picture of atmospheric structure, and it appears that thermal excitation must be the principal agent. However, our knowledge of the heat input from different sources is insufficient to permit describing average large-scale circulation or the average daily variations to be expected. The effects of large-scale circulation and eddy mixing on the composition of the thermosphere must still be studied in detail.

As expected, the new results bring new questions and cause reformulation of others. What is the latitudinal distribution of atmospheric temperature, and how does it vary? What is the global distribution of the neutral species? What are the characteristics of the hydrogen flow around the Earth? How can the D-region ionization be compatible with the recently obtained fluorescence measurements of nitric oxide? What is the spatial distribution of the diurnal density bulge? What is the average character of the large-scale circulation of the upper atmosphere?

With improved instrumentation and a greater variety of rockets and satellites available, answers to many of the questions raised above may be expected as the solar maximum is approached.

One of the important results of airglow studies in recent years has been the discovery of Lyman-alpha radiation from atomic hydrogen. About 85 percent of the radiation is caused by telluric hydrogen, the remainder of extraterrestrial hydrogen. The intensity of Lyman-alpha radiation shows a slow decrease with altitude, consistent with scattering in a geocorona. In contrast, the 1304 Å oxygen line has been found to show a broad maximum at about 180 kilometers. The reason for this is not understood. Laboratory and rocket studies have led to a change in the theory of the oxygen green-line emission, from that of a three-body reaction to a two-step process.

Progress has been made in studying the energy input of auroras and in the relation of auroral particles to the Van Allen belt. Contrary to the thinking of several years ago, it now appears that at least some of the Van Allen radiation (at least at high latitudes) is a result, rather than the cause, of auroral phenomena. Energetic electrons have been identified with bright auroral emission, while the diffuse and extensive auroras are excited by protons. Progress has also been made in understanding auroral electrojets, although the details are not entirely clear.

While the quantity of airglow and auroral data increases and the quality improves, there still remains the fundamental problem of uniquely relating the observational data to the physical processes occurring in the upper atmosphere. Significant breakthroughs in this regard are expected in the coming years from payloads such as the OGO–C, OGO–D, and OGO–F (POGO), which permit simultaneous *in situ* measurements of the intensity of airglow and auroras, the emission lines produced, the neutral- and charged-particle concentrations, and the solar emission. The experimental measurements are backed up by intensive theoretical and laboratory efforts to examine the various excitation mechanisms, and to measure reaction-rate coefficients and radiative lifetimes of pertinent reactions.

A considerable extension of our knowledge of interplantetary dust became possible with the advent of space research. Direct measurements of particles from 10^{-7} to 10^{-12} gram have been made. Satellite results have provided evidence for the existence of meteor streams. Little progress has been made in defining the structure, composition, and origin of these particles. The impact rate of the top of the Earth's atmosphere is about 6×10^{-6} particles/m^2/sec/sr. The rate diminishes by about five orders of magnitude for measurements in interplanetary space, remote from the vicinity of the Earth. Near the Earth, the penetration of thin structural materials has been found to be about 3×10^{-8} penetrations m^2/sec for the 25 μ thicknesses.

A great deal of practical concern exists regarding the penetration hazard from meteoroids. Our present knowledge of the peneration properties of meteoroids or of flux rates is insufficient to permit more than broadly qualitative answers at this time. However, a start has been made in obtaining penetration data through direct measurements by satellites. The source of zodiacal light is now believed to be the scattering of sunlight by interplanetary dust. Meteoric dust with a diameter of a few tenths of a micron has been found in noctilucent clouds. Future experiments will improve our knowledge of the spatial density, mass distribution, velocity, and charge of interplanetary dust particles. Identification of composition presents a more formidable and challenging problem.

The atmosphere of Mars is a current example of a case in which our thinking has undergone radical revision in the last several years. The present estimates of surface pressure are from 10 to 30 millibars, compared with the earlier accepted value of about 85 millibars. This difference places a severe restriction upon the weight of scientific instruments that can be carried by a soft-landing, survivable capsule. It is a most urgent problem to define the surface pressure and scale height of the Martian atmosphere as soon as possible. The ground-based observational and spectroscopic studies conducted during the 1964–65 opposition and the Mariner IV occultation experiment should contribute to resolving this problem. The characteristics of the winds and motions of the Martian atmosphere are also problems of immediate practical importance for successful capsule landings.

Estimates of the atmosphere of Venus have also undergone radical revision in recent years. Microwave observations from the Earth, spectroscopic data, and IR and microwave radiometers on Mariner II have all indicated considerably higher temperatures than the 285° K value accepted until about 1958. At present, it appears that the surface temperature of Venus may be in the vicinity of 700° K and that the surface pressure is somewhere in the range of 5 to 100 atmospheres. Carbon dioxide has been shown to be a prominent constituent of the atmosphere, and some water vapor exists. Quite recently, it has been found that the haze or cloud particles have the spectral characteristics of ice. Today, the atmosphere of Venus presents some of the most intriguing scientific questions with respect to its origin, composition, and physical characteristics.

References

1. SPITZER, L.: The Terrestrial Atmosphere Above 300 km. Atmospheres of the Earth and Planets (G. P. Kuiper ed.) University of Chicago Press, 1949, p. 213.
2. NICOLET, M.; AND AIKEN, A. C.: The Formation of the D Region of the Ionosphere. J. Geophys. Res., vol. 65, 1960, pp. 1469–1483.
3. KALLMAN, BIJL, H. K.: Daytime and Nighttime Atmospheric Properties Derived From Rocket and Satellite Observations. J. Geophys. Res., vol. 66, 1961, pp. 787-795.
4. JOHNSON, F. S.: Structure of the Upper Atmosphere. Satellite Environment Handbook. Second ed. (F. S. Johnson, ed.), Stanford Univ. Press, 1965, pp. 3–20.
5. JACCHIA, L. G.; AND SLOWEY, J.: Atmospheric Heating in the Auroral Zones: A Preliminary Analysis of the Atmospheric Drag of the Injun 3 Satellite. J. Geophys. Res., vol. 69, 1964, pp. 905–910.
6. HARRIS, I.; AND PRIESTER, W.: Relation Between Theoretical and Observational Models of the Upper Atmosphere. J. Geophys. Res., vol. 68, 1963, 5891–5894.
7. PAETZOLD, H. K.: Solar Activity in the Upper Atmosphere Deduced From Satellite Observations. Space Research III (W. Priester, ed.), North-Holland Pub. Co., 1963, pp. 28–52.
8. JACCHIA, L. G.: Electromagnetic and Corpuscular Heating of the Upper Atmosphere. Space Research III (W. Priester, ed.), North-Holland Pub. Co., 1963, pp. 3–18.
9. KING-HELE, D. G.: Decrease in Upper Atmosphere Density Since the Sunspot Maximum of 1957–58. Nature, vol. 198, 1963, pp. 832–834.
10. BLAMONT, J. E.; AND LORY, M. L.: New Direct Measurement of Ionospheric Temperature. Rocket and Satellite Meteorology (H. Wexler and J. E. Caskey, Jr., eds.), North-Holland Pub. Co., 1963, pp. 71–75.
11. NICOLET, M.: Solar Radio Noise Flux and Temperature of the Upper Atmosphere. J. Geophys. Res., vol. 68, 1963, pp. 6121–6144.

12. JACCHIA, L. G.: A Variable Density Model From Satellite Accelerations. J. Geophys. Res., vol. 65, 1960, pp. 2775–2782.
13. JOHNSON, F. S.: Circulation at Ionospheric Levels. Paper presented at 13th Gen. Assem., Int. Union Geod. and Geophys., Berkeley, Calif., 1963.
14. HANSON, W. B.; AND JOHNSON, F. S.: Electron Temperatures in the Ionosphere. Memoires, Soc. Roy. Sci., Liege, vol. 4, 1961, pp. 390–424.
15. DALGARNO, A.; MCELROY, M. B.; AND MOFFETT, R. J.: Electron Temperatures in the Ionosphere. Planet. Space Sci., vol. 11, 1963, pp. 463–484.
16. HANSON, W. B.: Electron Temperatures in the Upper Atmosphere. Space Research III (W. Priester, ed.), North-Holland Pub. Co., 1963, pp. 282–302.
17. SPENCER, N. W.; BRACE, L. H.; AND CARIGNAN, G. R.: Electron Temperature Evidence for Non-Thermal Equilibrium in the Ionosphere. J. Geophys. Res., vol. 67, 1962, pp. 157–175.
18. BRACE, L. H.; SPENCER, N. W.; AND DALGARNO, A.: Electrostatic Probe Data and Interpretation. Trans. Am. Geophys. Union, vol. 45, 1964, p. 82.
19. EVANS, J. V.: Ionospheric Temperatures During the Launch of NASA Rocket 8.14 on July 2, 1963. J. Geophys. Res., vol. 69, 1964, pp. 1436–1444.
20. BOWLES, K. L.: Equatorial Electron Density Profiles to 5000 km, Using the Incoherent Scatter Technique. Space Research III (W. Priester, ed.), North-Holland Pub. Co., 1963, pp. 253–264.
21. JONES, L. M.; PETERSON, J. W.; SCHAEFFER, E. J.; AND SCHULTER, H. F.: Upper-Air Density and Temperature: Some Variations and an Abrupt Warming in the Mesosphere. J. Geophys. Res., vol. 64, 1959, pp. 2331–2340.
22. STROUD, W. G.; NORDBERG, W.; BANDEEN, W. R.; BARTMAN, F. L.; AND TITUS, P.: Rocket-Grenade Measurements of Temperatures and Winds in the Mesosphere Over Churchill, Canada. J. Geophys. Res., vol. 65, 1960, pp. 2307–2323.
23. HESSTVEDT, E.: Note on the Nature of Noctilucent Clouds. J. Geophys. Res., vol. 66, 1961, pp. 1965–1987.
24. JOHNSON, F. S.: Temperatures in the High Atmosphere. Ann. Geophys., vol. 14, 1958, pp. 94–108.
25. JOHNSON, F. S.: Atmospheric Structure. Astronaut., vol. 7, no. 8, 1962, pp. 54–61.

26. Nicolet, M.: Density of the Heterosphere Related to Temperature. Smithsonian Astrophys. Obs. Spec. Rep. No. 75, 1961.
27. Harris, I.; and Priester, W.: Heating of the Upper Atmosphere. Space Research III (W. Priester, ed.), North-Holland Pub. Co., 1963, pp. 53–75.
28. Johnson, F. S.; and Fish, R. A.: The Telluric Hydrogen Corona. Astrophys. J., vol. 131, 1960, pp. 502–505.
29. Kupperian, J. E., Jr.; Byram, E. T.; Chubb, T. A.; and Friedman, H.: Far Ultraviolet Radiation in the Night Sky. Planet. Space Sci., vol. 1, 1959, pp. 3–6.
30. Bates, D. R.; and Nicolet, M.: The Photochemistry of Atmospheric Water Vapor. J. Geophys. Res., vol. 55, 1950, pp. 301–327.
31. Öpik, E. J.; and Singer, S. F.: Distribution of Density in a Planetary Exosphere, II. Physics Fluids, vol. 4, 1961, pp. 221–233.
32. Chamberlain, J. W.: Planetary Coronae and Atmospheric Evaporation. Planet. Space Sci., vol. 11, 1963, pp. 901–960.
33. Morton, D. C.; and Purcell, J. P.: Observations of the Extreme Ultraviolet Radiation in the Night Sky Using an Atomic Hydrogen Filter. Planet. Space Sci., vol. 9, 1962, pp. 455–458.
34. Patterson, T. N. L.; Johnson, F. S.; and Hanson, W. B.: The Distribution of Interplanetary Hydrogen. Planet. Space Sci., vol. 11, 1963, pp. 767–778.
35. Jacchia, L. G.: Satellite Drag During the Events of November 1960. Space Research II (H. C. van de Hulst, C. de Jager, and A. F. Moore, eds.), North-Holland Pub. Co., 1961, pp. 747–750.
36. Nicolet, M.: Helium, an Important Constituent in the Upper Atmosphere. J. Geophys. Res., vol. 66, 1961, pp. 2263–2264.
37. Hanson, W. B.: Upper Atmosphere Helium Ions. J. Geophys. Res., vol. 67, 1962, pp. 183–188.
38. Hale, L. C.: Ionospheric Measurements With a Multigrid Retarding Potential Analyzer. J. Geophys. Res., vol. 66, 1961, p. 1554.
39. Johnson, F. S.: Structure of the Upper Atmosphere. Satellite Environment Handbook (F. S. Johnson, ed.), Stanford Univ. Press, 1961, pp. 9–24.
40. Kocharts, G.; and Nicolet, M.: L'Helium et l'Hydrogène Atomique au Cours d'un Minimum d'Activité Solaire. Ann. Geophys., vol. 19, 1963, pp. 370–385.

41. HANSON, W. B.; AND PATTERSON, T. N. L.: Diurnal Variations of Hydrogen Concentration in the Exosphere. Planet. Space Sci., vol. 11, 1963, pp. 1035–1052.
42. DONAHUE, T. M.; AND MCAFEE, J. R.: Influence of Lateral Flow on the Diurnal Variation in Exospheric Hydrogen. Plant. Space Sci., vol. 12, 1964, pp. 1045–1054.
43. BATES, D. R.; AND PATTERSON, T. N. L.: Hydrogen Atoms and Ions in the Thermosphere and Exosphere. Planet. Space Sci., vol. 5, 1961, pp. 257–273.
44. BATES, D. R.; AND MCDOWELL, M. R. C.: Escape of Helium. J. Atm. Terr. Phys., vol. 16, 1959, pp. 393–394.
45. JOHNSON, F. S.; AND WILKINS, E. M.: Thermal Upper Limit on Eddy Diffusion in the Mesosphere and Lower Thermosphere. J. Geophys. Res., vol. 70, no. 6, Mar. 1965, p. 1281.
46. MACDONALD, G. J. F.: The Escape of Helium From the Earth's Atmosphere. Rev. Geophys., vol. 1, 1963, pp. 305–349.
47. BARTH, C. A.: Rocket Measurement of the Nitric Oxide Dayglow. J. Geophys. Res., vol. 69, 1964, pp. 3301–3303.
48. SCHAEFFER, E. J.: The Dissociation of Oxygen Measured by a Rocket-borne Mass Spectrometer. J. Geophys. Res., vol. 68, 1963, pp. 1175–1176.
49. NIER, A. O.; HOFFMAN, J. H.; JOHNSON, C. Y.; AND HOLMES, J. C.: Neutral Composition of the Atmosphere in the 100- to 200-Kilometer Range. J. Geophys. Res., vol. 69, 1964, pp. 979–989.
50. NICOLET, M.: Les Variations de la Densité et du Transport de Chaleur par Conduction dans l'Atmosphère Supérieure. Space Research (H. K. Kallmann Bijl, ed.), North-Holland Pub. Co., 1960, pp. 46–89.
51. LILLER, W.; AND WHIPPLE, F. L.: High-Altitude Winds by Meteor-Trail Photography. Rocket Exploration of the Upper Atmosphere (R. L. F. Boyd and M. J. Seaton, eds.), Pergamon Press, Ltd., 1954, pp. 112–130.
52. ROSENBERG, N. W.; AND EDWARDS, H. D.: Observations of Ionospheric Wind Patterns Through the Night. J. Geophys. Res., vol. 69, 1964, pp. 2819–2826.
53. KOCHANSKI, A.: Atmospheric Motions From Sodium Cloud Drifts. J. Geophys. Res., vol. 69, 1964, pp. 3651–3662.
54. BLAMONT, J.: Turbulence in Atmospheric Motion Between 90 and 130 km of Altitude. Planet. Space Sci., vol. 10, 1963, pp. 89–101.
55. HINES, C. O.: Internal Atmospheric Gravity Waves at Ionospheric Height. Can. J. Phys., vol. 38, 1960, pp. 1441–1481.

56. Pitteway, M. L. V.; and Hines, C. O.: The Viscous Damping of Atmospheric Gravity Waves. Can. J. Phys., vol. 41, 1963, pp. 1935–1948.
57. Axford, I.: The Formation and Vertical Movement of Dense Ionized Layers in the Ionosphere Due to Neutral Wind Shears. J. Geophys. Res., vol. 68, 1963, pp. 769–779.
58. Jackson, J. E.; and Seddon, J. C.: Ionosphere Electron-Density Measurements With the Navy Aerobee-Hi Rocket. J. Geophys. Res., vol. 63, 1958, pp. 197–208.
59. Knudsen, W. C.; and Sharp, G. W.: Evidence for Temperature Stratification in the E Region. J. Geophys. Res., vol. 70, 1965, pp. 143–160.
60. Fejer, J. A.: Atmospheric Tides and Associated Magnetic Effects. Rev. Geophys., vol. 2, 1964, pp. 275–309.
61. Johnson, F. S.: Pressure and Temperature Equalization at 200-Km Altitude. J. Geophys. Res., vol. 65, 1960, pp. 2227–2232.
62. Purcell, J. P.; and Tousey, R.: The Profile of Solar Hydrogen Lyman-Alpha. J. Geophys. Res., vol. 65, 1960, pp. 370–372.
63. Donahue, T. M.; and Thomas, G.: Distribution of Hydrogen in the Outer Atmosphere. Planet. Space Sci., vol. 10, 1963, pp. 65–77.
64. Fastie, W. G.; Crosswhite, H. M.; and Heath, D. F.: Rocket Spectrophotometer Airglow Measurements in the Far Ultraviolet. J. Geophys. Res., vol. 69, 1964, pp. 4129–4140.
65. Zipf, E. C.; and Fastie, W. G.: An Observation of the (0,0) Negative Band of N_2^+ in the Dayglow. J. Geophys. Res., vol. 69, 1964, pp. 2357–2368.
66. Fastie, W. G.; and Crosswhite, H. M.: Far U.V. Dayglow Measurements: Atomic Oxygen. Planet. Space Sci., vol. 12, 1964, pp. 1021–1026.
67. Chapman, S.: Some Phenomena of the Upper Atmosphere. Proc. Roy. Soc. (London), vol. A132, 1931, pp. 353–374.
68. Barth, C. A.; and Hildebrandt, A. F.: The 5577 Å Airglow Emission Mechanism. J. Geophys. Res., vol. 66, 1961, pp. 935–987.
69. Young, R. A.; and Clark, K. C.: Rate of the Three-Body Atomic Oxygen Reaction for the Excitation of the Airglow OI (5577 Å) Line. Phys. Rev. Letters, vol. 5, 1960, pp. 320–321.
70. Barth, C. A.: Three-Body Reactions. Ann. Geophys., vol. 20, 1964, pp. 182–196.

208–028 O—66——5

71. Barbier, D.: Nouvelles Observations de la Raie Rouge du Ciel Nocturne en Afrique. Ann. Geophys., vol. 20, 1964, pp. 22–33.
72. Fastie, W. G.; Crosswhite, H. M.; and Markham, T. P.: Far Ultraviolet Auroral Spectra With a Rocket Ebert Spectrophotometer. Ann. Geophys., vol. 17, 1961, pp. 109–115.
73. Omholt, A.: Studies on the Excitation of Aurora Borealis, I. The Hydrogen Lines. Geophys. Publikasjoner, vol. 20, 1959, pp. 1–40.
74. Davis, L. R.; Berg, O. E.; and Meredith, L. H.: Direct Measurement of Particle Fluxes in and Near Auroras. Space Research (H. K. Kallmann Bijl, ed.), North-Holland Pub. Co., 1960, pp. 721–735.
75. McIlwain, C. E.: Direct Measurements of Particles Producing Visible Auroras. J. Geophys. Res., vol. 65, 1960, pp. 2727–2747.
76. Dessler, A. J.; and O'Brien, B. J.: Penetrating Particle Radiation. Satellite Environment Handbook. Second ed. (F. S. Johnson, ed.), Stanford Univ. Press, 1965, pp. 54–92.
77. Chamberlain, J. W.: Physics of the Aurora and Airglow. Academic Press, 1961, p. 251.
78. Fejer, J. A.: Theory of Auroral Electrojets. J. Geophys. Res., vol. 68, 1963, pp. 2147–2157.
79. Levin, B. Yu.: Fragmentation of Meteoric Bodies. Soviet Astron.—AJ, vol. 7, 1963, pp. 233–242.
80. Whipple, F. L.: The Meteoric Risk to Space Vehicles. Vistas in Astronautics. M. Alperin and M. Stern, eds., Pergamon Press, 1958, pp. 115–124.
81. Whipple, F. L.: On Meteoroids and Penetration. J. Geophys. Res., vol. 68, 1963, pp. 4929–4939.
82. McCracken, C. W.; Alexander, W. M.; and Dubin, M.: Direct Measurements of Interplanetary Dust Particles in the Vicinity of Earth. Nature, vol. 192, 1961, pp. 441–442.
83. Dubin, M.; and McCracken, C. W.: Measurements of Distributions of Interplanetary Dust. Astron. J., vol. 67, 1962, pp. 248–256.
84. Manring, E. R.: Micrometeorite Measurements From 1958 Alpha and Gamma Satellites. Planet. Space Sci., vol. 1, 1959, pp. 27–31.
85. Berg, O. E.; and Meredith, L. H.: Meteoric Impacts to Altitude of 103 Kilometers. J. Geophys. Res., vol. 61, 1956, pp. 751–754.

86. HASTINGS, E. C., JR.: The Explorer XVI Micrometeoroid Satellite. Supplement I, Preliminary Results for the Period January 14, 1963, through March 2, 1963. NASA TM X-824, 1963.
87. D'AIUTOLO, C. T.: Review of Meteoroid Environment Based on Results From Explorer XIII and Explorer XVI Satellite. Space Research IV (P. Muller, ed.), North-Holland Pub. Co., 1964, pp. 858–874.
88. HEMENWAY, C. L.; AND SOBERMAN, R. K.: Studies of Micrometeorites Obtained From a Recoverable Sounding Rocket. Astron. J., vol. 67, 1962, pp. 256–266.
89. VEDDER, J. F.: Micrometeoroids. Satellite Environment Handbook. Second ed., F. S. Johnson, ed., Stanford Univ. Press, 1965, pp. 109–124.
90. WHIPPLE, F. L.: The Dust Cloud about the Earth. Nature, vol. 189, 1961, pp. 127–128.
91. ALEXANDER, W. M.; MCCRACKEN, C. W.; AND LA GOW, H. E.: Interplanetary Dust Particles of Micron-Size Probably Associated With the Leonid Meteor Stream. J. Geophys. Res., vol. 66, 1961, pp. 3970–3973.
92. BEHR, A.; AND SIEDENTOPF, H.: Untersuchen über Zodiakallicht und Gegenschein nach lichtelektrischen Messungen auf dem Jungfraujoch. Z. Astrophys., vol. 32, 1953, pp. 19–50.
93. BLACKWELL, D. E.: The Zodiacal Light and Its Interpretation. Endeavor, vol. 19, 1960, pp. 14–19.
94. BEGGS, D. W.; BLACKWELL, D. E.; DEWHIRST, D. W.; AND WOLSTENCROFT, R. D.: Further Observations of the Zodiacal Light From a High Altitude Station and Investigation of the Interplanetary Plasma, II. Spectrophotometric Observations and the Electron Density in Interplanetary Space. Mon. Notes, Roy. Astron. Soc., vol. 127, 1964, pp. 329–340.
95. DEIRMENDJIAN, D.; AND VESTINE, E. H.: Some Remarks on the Nature and Origin of Noctilucent Cloud Particles. Planet. Space Sci., vol. 1, 1959, pp. 146–153.
96. HEMENWAY, C. L.; SOBERMAN, R. K.; AND WITT, G.: Sampling of Noctilucent Cloud Particles. Tellus, vol. 16, 1964, pp. 84–88.
97. DE VAUCOULEURS, G.: Physics of the Planet Mars. Faber & Faber, Ltd., London, 1954, p. 365.
98. DOLLFUS, A.: Polarization Studies of Planets. The Solar System, III. Planets and Satellites (G. P. Kuiper and B. M. Middlehurst, eds.), Univ. of Chicago Press, 1961, pp. 343–399.

99. KUIPER, G. P.: Infrared Spectra of Stars and Planets, IV. The Spectrum of Mars, 1–2.5 Microns, and the Structure of Its Atmosphere. Lunar and Planetary Laboratory Communications, No. 31, Univ. of Arizona, 1964.
100. KAPLAN, L. D.; MÜNCH, G.; AND SPINRAD, H.: An Analysis of the Spectrum of Mars. Astrophys. J., vol. 139, 1964, pp. 1–15.
101. DANIELSON, R. E.; GAUSTAD, J. E.; SCHWARZSCHILD, M.; WEAVER, H. E.; AND WOOLF, N. J.: Mars Observations From Stratoscope II. Astron. J., vol. 69, 1964, pp. 344–352.
102. SAGAN, C.: The Abundance of Water Vapor on Mars. Astron. J., vol. 66, 1961, p. 52.
103. MAYER, C. H.; MCCULLOUGH, T. P.; AND SLOANMAKER, R. M.: Observations of Venus at 3.14-cm Wave Length. Astrophys. J., vol. 127, 1958, pp. 1–10.
104. KELLOGG, W. W.; AND SAGAN, C.: The Atmospheres of Mars and Venus. Pub. No. 944, Space Science Board, Nat. Acad. Sci., Washington, D.C., 1961, p. 151.
105. DRAKE, F. D.: 10-cm Observations of Venus in 1961. Pub. Nat. Radio Astron. Observ., vol. 1, no. 11, 1962, pp. 165–178.
106. SPINRAD, H.: Spectroscopic Temperatures and Pressure Measurements in the Venus Atmosphere. Pub. Astron. Soc. Pac., vol. 74, 1962, pp. 187–201.
107. SPINRAD, H.: A Search for Water Vapor and Trace Constituents in the Venus Atmosphere. Icarus, vol. 1, 1962, pp. 266–270.
108. BOTTEMA, M.; PLUMMER, W.; AND STRONG, J.: Water Vapor in the Atmosphere of Venus. Astrophys. J., vol. 140, 1964, pp. 1021–1022.
109. BOTTEMA, M.; PLUMMER, W.; STRONG, J.; AND YANDER, R.: Composition of the Clouds of Venus. Astrophys. J., vol. 140, 1964, pp. 1640–1641.
110. PETTENGILL, G. H.: Radar Measurements of Venus. Space Research III (W. Priester, ed.), North-Holland Pub. Co., 1963, pp. 872–885.
111. VICTOR, W. K.; AND STEVENS, R.: The 1961 JPL Venus Radar Experiment. Space Research III (W. Priester, ed.), North-Holland Pub. Co., 1963, pp. 886–890. Also IRE Professional Group on Space Electronics and Telemetry, SET–8, 1962, pp. 84–97.
112. GOLDSTEIN, R. M.: Radar Studies of the Planets. Rev. Geophys., vol. 2, 1964, pp. 579–592.

113. MINTZ, Y.: The Energy Budget and Atmospheric Circulation on a Synchronously Rotating Planet. Icarus, vol. 1, 1962, pp. 172–173.

114. DRAKE, F. D.: 10-Cm Observations of Venus Near Superior Conjunction. Nature, vol. 195, 1962, p. 894.

115. CHASE, S. C.; KAPLAN, L. D.; AND NEUGEBAUER, G.: The Mariner II Infrared Radiometer Experiment. J. Geophys. Res., vol. 68, 1963, pp. 6157–6169.

116. BARATH, F. T.; BARRETT, A. H.; COPELAND, J.; JONES, D. E.; AND LILLEY, A. E.: Microwave Radiometers. Science, vol. 139, 1963, pp. 908–909.

117. BARATH, F. T.; BARRETT, A. H.; COPELAND, J.; JONES, D. E.; AND LILLEY, A. E.: Mariner II Microwave Radiometer Experiment and Results. Astron. J., vol. 69, 1964, pp. 49–58.

118. BARRETT, A. H.; AND STAELIN, D. H.: Radio Observations of Venus and the Interpretations. Space Sci. Rev., vol. 3, 1964, pp. 109–135.

119. SAGAN, C.: The Physical Environment of Venus: Models and Prospects. Space Age Astronomy (A. J. Deutsch and W. B. Klemperer, eds.), Academic Press, 1962, pp. 430–442.

120. KUIPER, G. P.: Planetary Atmospheres and Their Origins. The Atmospheres of the Earth and Planets (G. P. Kuiper, ed.), Univ. of Chicago Press, 1952, pp. 306–405.

121. KIESS, C. C.; CORLISS, C. H.; AND KIESS, H. K.: High Dispersion Spectra of Jupiter. Astrophys. J., vol. 132, 1960, pp. 221–231.

122. SPINRAD, H.: Spectroscopic Research on the Major Planets. Appl. Optics, vol. 3, 1964, pp. 181–186.

123. BAUM, W. A.; AND CODE, A. D.: A Photometric Observation of the Occultation of δ Arietis by Jupiter. Astron. J., vol. 58, 1953, pp. 108–112.

124. SPINRAD, H.; AND TRAFTON, L. M.: High Dispersion Spectra of the Outer Planets. 1. Jupiter in the Visual and Red. Icarus, vol. 2, 1963, pp. 19–28.

125. ÖPIK, E. J.: Jupiter: Chemical Composition, Structure, and Origin of a Giant Planet. Icarus, vol. 1, 1962, pp. 200–257.

126. ZABRISKIE, F.: Hydrogen Content of Jupiter's Atmosphere. Astron. J., vol. 67, 1962, pp. 168–170.

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